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A STUDY TO DETERMINE THE HYDROLOGIC AND PHYSICAL PROPERTIES OF SOME BEAVER CREEK SOILS

Final Report

A Cooperative Study Between the

University of Arizona

And the

Rocky Mountain Forest and Range Experiment Station

INTRODUCTION

This report complets A Study to Determine the Hydrologic and Physical Properties of Some Beaver Creek Soils. Several interrelated sections are presented on different portions of the project undertaken principally by graduate students in the Department of Watershed Management at the University of Arizona. As in most broad projects of this nature several significant new findings are reported, the applicability of some generally accepted practices to specific situations found in the study are questioned, needs for future research pointed up and approaches to some of the problems in the Beaver Creek area suggested. By no means have all possible conclusions been drawn nor analyses of the mass of data collected in the study exhausted. It is hoped that in studying the report further application of results can be found to the many soil-water problems which appear unique to the Beaver Creek Watersheds.

DEVIATIONS FROM THE STUDY PLAN

The three major objectives outlined in the study plan have been met in the studies reported herein. The objectives were:

1) To described the physical properties and hydrologic characteristics of the soils on several Beaver Creek watersheds and their variation within, and range between soil types.
2) To develop a sampling model to specifically guide sampling of the remaining Beaver Creek watersheds which will serve as a general guide for soil sampling in the area.
3) To develop methods for characterizing the hydraulic behavior of Beaver Creek soils by correlating the saturated conductivity and the unsaturated sorptivity of the measured physcial properties.

Accomplishments under objectives 1 and 2 are reported in Section 5. A sampling model is presented in this section and a simplified guide developed from the model is presented in Section 10. Soil physical property measurements are given in the appendix. Accomplishments under objective 3 are presented in Section 6. Other sections report on associated work accomplished in addition to the stated objectives.

The following lists deviations from the methods listed in the original study plan.

1) Sampling depths - The number of sampling depths were increased. Instead of sampling the 0-6 inch layer, the 0-3 and 3-6 inch depth were sampled separately. Other depths were sampled as stated in the study plan.

2) <u>Bulk Density</u> - Bulk density was determined on undisturbed air dried clods as outlined. The sand cone method which was to be used by Forest Service personnel for comparison purposes was never employed.

3) <u>Specific gravity</u> - Specific gravity was extremely uniform between soils at the depths sampled. Therefore determinations were made on ten samples drawn at random from each of the major soil series.

4) <u>Soil Water Suction</u> - Determined at .33, .66, 3, 5, 10, and 15 bars, but not at .1 bar because of the high water holding capacity of the soils and pressure plate impedance which lead to unrealistic retention values.

5) <u>Conductivity</u> - Determined for the 0-3 inch layer of soil. For deeper depths using confined soil cores, water movement under ordinary pressures was too small for reliable measurements. Accordingly, a separate study on the permeability of subsoils was made and is reported in Section 7. Because of the extreme swelling nature of the Beaver Creek soils, permeability tests on unconfined clod or block samples were not possible.

6) <u>Texture</u> - Determined as outlined.

7) <u>Total water holding capacity</u> - May be readily determined by routine methods from the data presented.

8) <u>Organic Matter</u> - Determined as outlined.

9) <u>Infiltration</u> - Determined as outlined.

10) Stoniness - To have been determined by Forest Service personnel but never completed. Accordingly, a small separate study on surface rock cover was made as reported in Section 9.

11) Soil profile descriptions - Determined by US Forest Service personnel as outlined.

12) Soil fertility - Determined as outlined.

RESULTS

The report contains 10 sections on different phases of the project each of which is presented as a separate entity.

Section 1

Maps of the watersheds showing the location of sampling pits are included in this section. Descriptions of the general study area may be found in Soil Survey Beaver Creek, Arizona. They are reitterated in Section 5 for the particular watersheds sampled in the study. The method of selecting sampling points using a previously established vegetation inventory scheme is also given in Section 5.

Section 2

Because of the large number of samples processed in the study laboratory techniques were streamlined to accomodate analyses. The methods described in this section were tested for precision and carried out as faithfully as humanly possible. Greatest difficulty was experienced with the high pressure suction apparatus. The soils when drying shrink away from any surface, thus the results of over 800 runs with a ceramic plate extractor had to be discarded. A membrane extractor with a differential diaphram pressure of 8 lbs. was necessary to obtain reasonably reproduceable results. Nevertheless, considerable variation exists in the high pressure data.

Results from the physical and chemical analysis of all samples are given in the appendix. Samples are identified for each watershed by vegetation inventory sample point number, depth and replication. Thus, a sample identified as 067 12-24 2 is the second replication of a sample taken at sample point 67 from the 12-24 inch depth.

Section 3

The profiles of all but a few pits sampled in the study were described by a Forest Service team of soil scientists. This section contains their descriptions as made in the field.

Section 4

An analysis is reported in this section made of the profile descriptions in order to determine if differences in some of the major soil series were outstanding. Undoubtedly subjective differences exist between soil series such as the Springerville and Brolliar series but from an objective or descriptive point of view as evidenced by the analysis they are not clearly defined. At the same time it is recognized that a much larger sample would be necessary before completely valid statistical tests could be made. However, possible implications to Watershed Management in the Beaver Creek area are in evidence and somewhat supported in Section 5 of this report.

Section 5

This section brings out a number of important features of soil variation on the Beaver Creek Watersheds. Three of the most important are: 1) the similarity between soil series in the soil properties measured, 2) the homogeneity of variances between soil series and 3) the 'macro-uniformity' phenomena.

The similarity found in soil physical properties between soil series indicates that where these properties are important to the hydrology of the watershed it may not be necessary to consider soil mapping units necessarily coincident with Watershed Management units. The homogeneity of variances that exist between soil mapping units in the properties measured indicate that stratification by soil mapping units may be unnecessary in the Beaver Creek area. This could result in considerable economizing for future sampling work in the area.

The macrouniformity phenomena found, wherein variation between adjacent points is greater than variation between widely seperated points, could also lead to economy in sampling but at the same time raises interesting questions. Economy in sampling efforts may be realized by taking more subsamples at a point rather than more points to achieve the same degree of precision. However, it also implies that the analyses generally accepted in most sampling studies in the past for other areas may not be valid in the Beaver Creek area. That variances on large watersheds was found as high as those on small watersheds may also be the result of this phenomena.

Section 6

Analysis of infiltration runs were made on the major soil series sampled in the study are reported in this section. It was found that the data conformed very closely to infiltration theory and that the paramaters necessary to describe the phenomena could be determined with a high degree of precision. These parameters could be related to the physical, chemical and genetic characteristics of the soils by regression analyses. In general, the relationships shown by the analyses were physically meaningful for the conditions

of the study. The equations developed may be used to estimate the probable maximum capacity of the soils in the Beaver Creek area to absorb water. However, they should be used only for conditions of antecedent moisture similar to those under which the study was made. Furthermore, because of the narrow range of the physcial characteristics in the Beaver Creek soils extension of the prediction equations, even to slightly different soils should not be made.

Section 7

This study was made to determine the water transmission characteristics of the subsoils of two typical Beaver Creek soil series. The study was made in the laboratory on prepared soil material. Since considerable natural mixing occurs under field conditions in the subsoils of these series as evidenced by numerous slickenslides, the artificial conditions of the laboratory may not have been unrealistic.

Two interrelated features of significance to Watershed Management in areas where these soils are found are brought out by the study -- the low permeabilities of the materials and the departure from proportional flow theory they exhibit. It was calculated that in the absence of cracks, root or other channels which might conduct water only about 8 gallons a day would actually be expected to pass through a 3 foot depth of these materials per acre if a 1 cm depth of water were maintained at the surface. The calculation takes into account the non-Darcy behavior of the materials. If hydrologic conductivities were determined in the usual manner (assuming Darcy flow) from one point on a curve of flow versus head, under the relatively high head necessary for such a determination, it may be calculated that under the same conditions about 500 gallons per day would pass through such a profile. The difference is difficult to ignore.

It is doubtful if similar discrepencies would be obtained with the structured surface soil materials where macro pores would be expected to transmit the major portion of the flow. Furthermore, because of the low permeabilities of the subsoil materials relative to the structured horizons above, interflow such as observed on Watershed 12 might be considerable.

Equation ( ) in this report, through completely empirical, appears to adequately describe the flow relationship found in the study for the subsoil materials. The equation is written:

$$\ln y = b_0 + b_1 \ln X + b_2 (\ln X)^2$$

However, the flow units are in $\frac{Cm^2}{A\text{-}min}$ and head is in cm of Hg. In order to convert flow to inches per hour per square inch for a hydraulic head expressed in inches it is necessary to 1) take inches of head (water) and multiply by 1.87 which will give head (x) in cm of Hg, 2) solve the equation, 3) multiply the analog of the flow rate (y) by .547 to get inches per hour.

Section 8

One of the most hydrologically significant features of the soils in the Beaver Creek area is their pronounced shrinking and swelling as they are dried or wetted. The study reported in this section was made in order to obtain some estimate of the phenomena and its probable courses. The study raises some pertinent questions on the relationships involved in the shrinking phenomena but more important points up the inadequacies of applying standard procedures of water budget accounting to the Beaver Creek soils.

For example, from the curve of Figure 1 it can be seen that an increase of about 50 percent in volume would be possible with complete wetting and that at this expanded volume the soil could hold about 66 percent water by weight. If 1.7 $gm\text{-}cm^{-3}$ is taken as the dry bulk density of the surface layer of the Springerville soil on Watershed 3, a 3-inch layer of dry soil material of this nature could conceivable hold about 4.5 inches of water. Under field conditions, of course, thorough wetting would most likely not be achieved and completely free expansion would not be possible. Neverthe-less considering the depth at which the soil normally dries and cracks on Watershed 3 under the hot dry climate of the area, more than enough shrinking and expansion is possible to account for all the annual precipitation that falls on the area.

Until some fundamental work is accomplished on the nature of swelling in the vertisols of the Beaver Creek area conclusion on the hydrology and management of the watersheds on which they are located will remain qualita-tive and subjective. The problem could be approached both from a mechanical or thermodynamic basis. It is our feeling that thermodynamic treatment holds considerable promise. A first step would require evaluation of the geometry term in the chemical potential equation; namely

$$\frac{\partial \bar{G}}{\partial \chi} d\chi$$

in the general equation

$$d\bar{G} = \frac{\partial \bar{G}}{\partial P_e} dP_e + \frac{\partial \bar{G}}{\partial T} dT + \frac{\partial \bar{G}}{\partial \theta} d\theta + \sum \left(\frac{\partial \bar{G}}{\partial \eta_2}\right) d\eta_2 + \frac{\partial \bar{G}}{\partial \chi} d\chi$$

Section 9

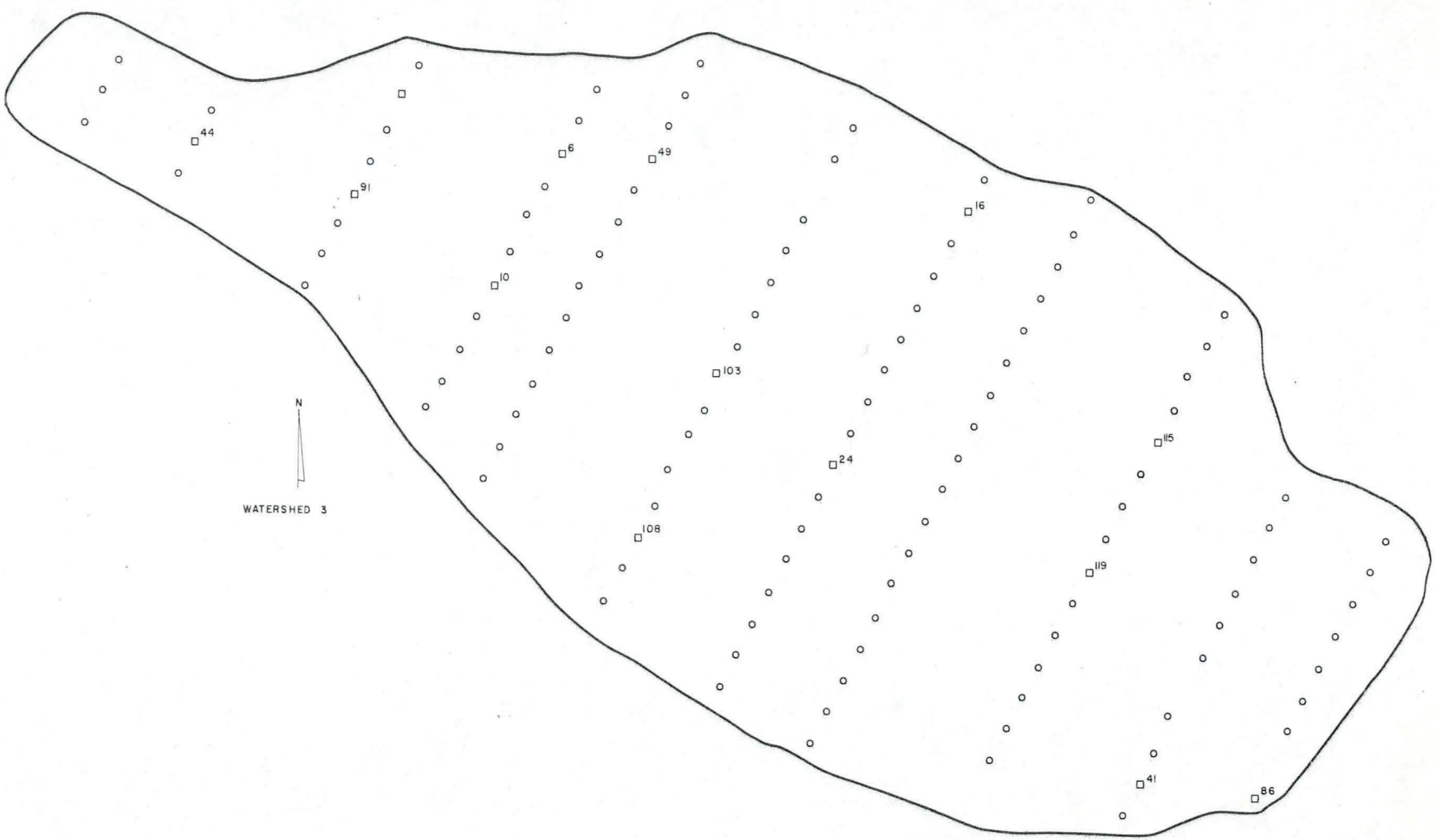
This section provides a means of describing the size distribution of rock cover on the Beaver Creek Watersheds. It is believed that such descriptions may be useful in the event mathematical models of surface runoff were to be developed for the area, otherwise the information might be used qualitatively in erosion studies or to explain possible hydrograph abnormalities. From the data presented it is possible to calculate the total surface rock cover. However, it should be pointed out that some areas of the watersheds have an almost complete pavement of rocks only thinly covered by soil. In this study only the exposed rocks were counted.

Section 10

This section presents a slide rule device for estimating the optimum number of sample points or subsamples to take for a given precision or for fixed costs. The purpose of the guide is to provide a first approximation of sampling needs for planning a sampling operation. It of course does not provide the best possible estimate. This would have to be determined during the sampling operation. An example of the use of the guide is given.

SECTION 1

LOCATION OF SOIL SAMPLING PITS



44
91
6
49
16
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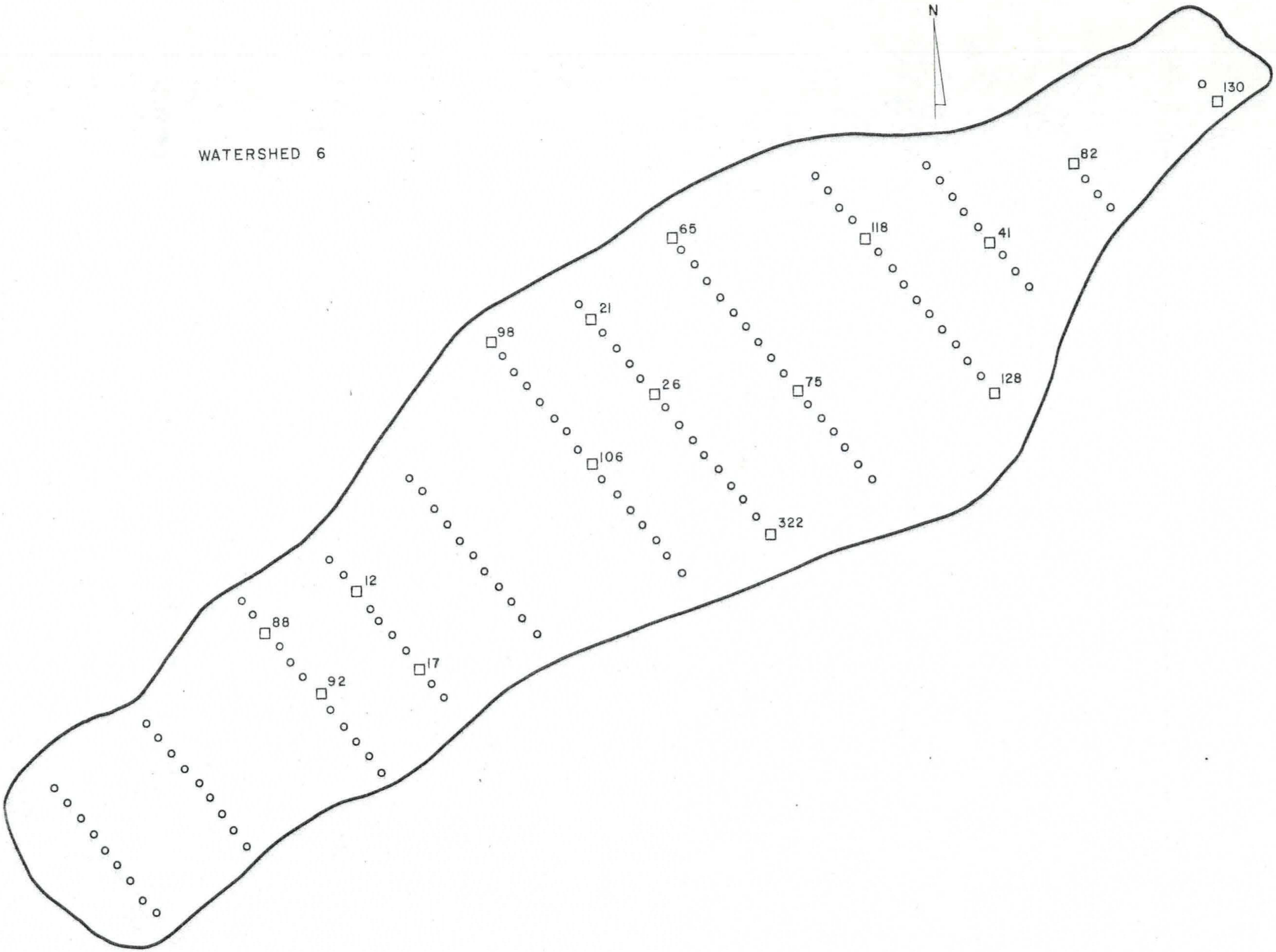
103
N
115
24
WATERSHED 3
108
119
41
86



N
WATERSHED 6
130
82
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118
41
21
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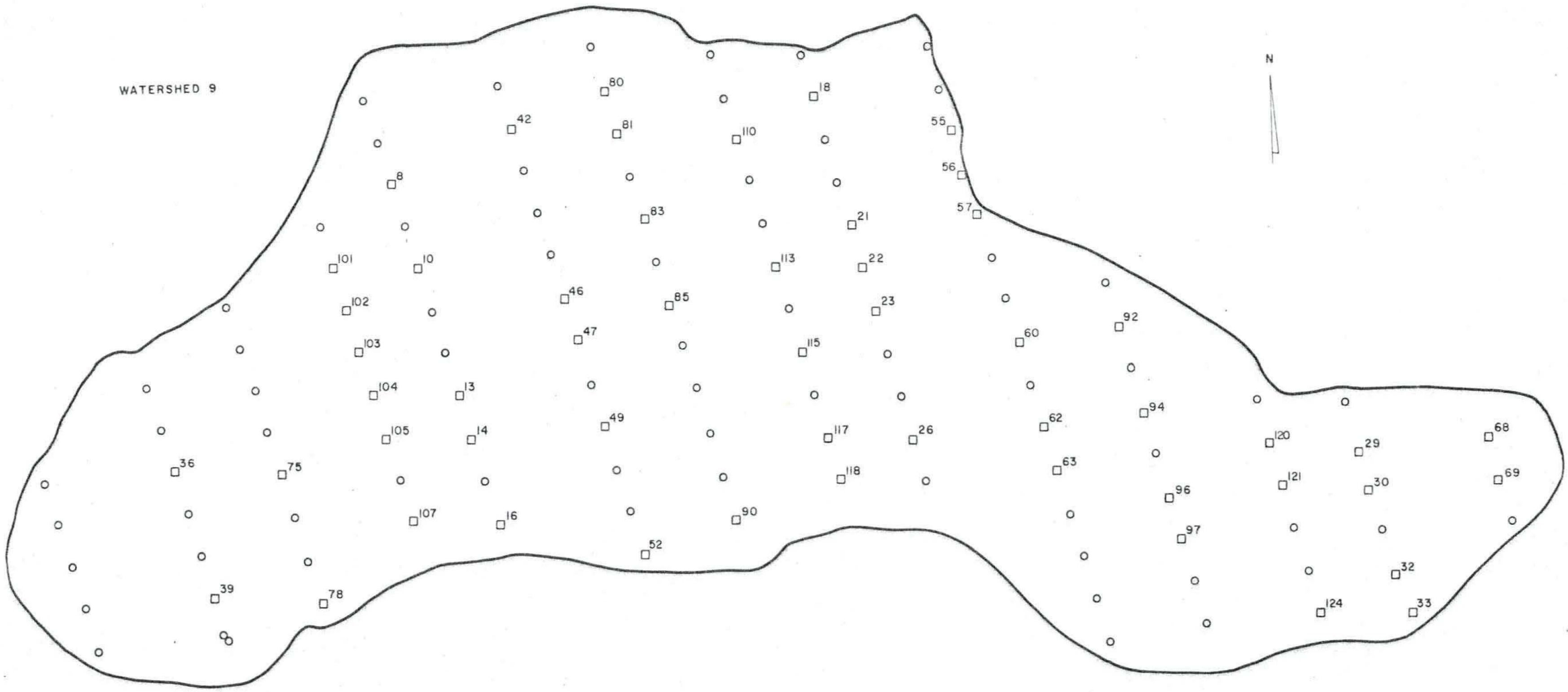
75
128
106
322
12
88
17
92


WATERSHED 9
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18
42
81
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8
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101
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22
102
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23
103
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124
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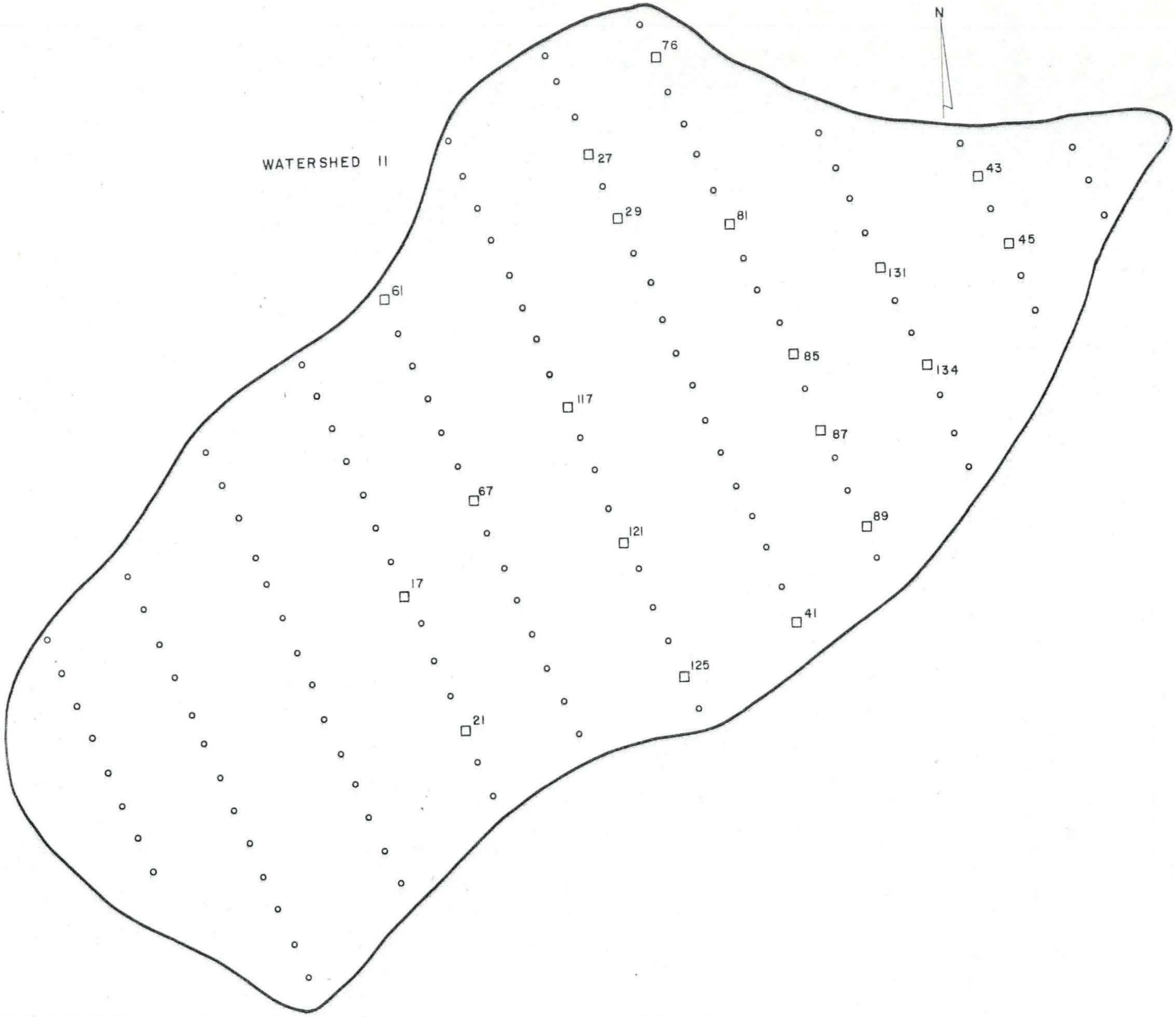

WATERSHED II
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76
27
29
81
43
45
131
61
85
134
117
87
67
89
121
17
41
125
21

SECTION 2

LABORATORY PROCEDURES FOR SOIL ANALYSIS

by

Rafaela M. Santa Cruz

To begin preparation of the soils each container was numbered by watershed, sample point, depth and replicate to facilitate handling. Then six undisturbed clods were removed from each quart container. The remaining soil was air dried, ground in a meat grinder, put through a two mm sieve, and run through a mechanical pulverizer in preparation for laboratory use. The soils were then tested for the following soil physical properties: bulk density, texture, organic matter, and soil-water-suction relationships. A chemical analysis included determination of the following: pH, soluble salts, nitrate, phosphate, and EDTA.

SOIL PHYSICAL ANALYSES

Bulk Density

Bulk density was determined by the parafin method. One undisturbed clod was taken from each soil container, labeled, and placed on a tray which contained about 35 clods. Each clod was then dipped in hot parafin maintained at about 70°C. The clods on three or four trays were dipped at one time. Each clod was then suspended in a beaker of water placed on a Mettler scale, and total weights recorded. Finally each clod was placed in a soil

can and oven dried (the wax seal was broken before placing in oven). The weight of each clod was then determined and recorded. Bulk density was then calculated from the raw data with the equation:

$$BD = W_1/W_2 - W_3 \tag{1}$$

where subscripts 1, 2, and 3 refer to the weight of oven dried soil, weight of water with clod and weight of water, respectively.

Texture

Texture was determined on disturbed sample material by Day's modification of the Bouyoucos method. The entire contents of each container were spread out on a countertop and two 40-gram samples composited from about 12 subsamples were weighed out and placed in soil cans. After 60 samples had been taken, 30 were transferred into 8 oz. bottles containing 50 ml of 10% calgon solution. The bottles were filled with distilled water, with enough space left to allow agitation. The bottles were then placed in a shaker and left shaking 15-18 hours (overnight) for dispersion. The remaining samples were over dried to determine dry weights.

The following day the contents of each bottle were transferred to a one liter graduated cylinder. The cylinders were then filled to the one liter mark with distilled water and placed in a uniform temperature bath. Each cylinder was agitated with a metal plunger, and hydrometer readings were also taken and recorded. Particle diameters and percentage sand, silt, and clay were calculated from the raw data sheets.

Soil Water-Suction Relationships

The entire contents of each container were spread out on a counter top. Random subsamples were taken and composited in a soil retention ring on a low pressure porous plate. An undisturbed clod of the same soil material was placed on top. This procedure was followed until a plate with 20-25 rings was filled. Each plate was soaked overnight to saturate the samples. The following day they were placed in a pressure plate extractor (4 plates at a time) and either 1/3 or 2/3 atmosphere of pressure was applied for 24 hours. Then the undisturbed samples were placed in soil cans and weighed. They were oven dried for at least 24 hours after which they were reweighed (cans were covered when not in oven to avoid moisture loss). Percentage moisture retained was calculated on the basis of weight lost.

For higher pressures (3, 5, 10, 15 atmospheres) only disturbed samples were used. All other procedures were identical, excepting the use of a high pressure membrane apparatus. A ceramic plate extractor could not be used because of the pronounced shrinking of the soil samples and subsequent breaking away from the plates.

Particle Density

Approximately 10 gms of air-dry soil were placed in a pycnometer. The weight of the pycnometer and soil was recorded. (Water content of soil was determined by air drying a duplicate soil sample.) The pycnometer was half filled with distilled water. The mixture was gently boiled for several minutes to remove entrapped air. When the pycnometers were cooled they were filled with more boiled, cooled, distilled water, and stoppers were inserted. After cleaning the outside of the pycnometer, it was weighed.

The temperature of the contents was taken. The weights of the pycnometer filled with air and filled with water had been previously determined. Particle density was then calculated from the following equation:

$$D_p = \frac{dw\ (W_s - W_a)}{(W_s - W_a) - (W_{sa} - W_w)} \tag{2}$$

where dw is the density of water in gm/cm^3 at observed temperature, W_s is the weight of the pycnometer plus soil sample, W_a is the weight of the pycnometer filled with air, W_{sa} is the weight of the pycnometer filled with soil and W_w is the weight of the pycnometer filled with water at temperature observed.

CHEMICAL ANALYSES

Saturation Extract

Reagents

A. .01-N CDTA

B. Alkaline ammonium chloride buffer (67.5 gm ammonium chloride dissolved in 250 ml of H_2O plus 570 ml concentrated ammonium hydroxide and enough H_2O to make 1 liter).

C. Calmagite (.2 gm Calmagite in 100 ml of H_2O).

D. .1 gm of methyl red dissolved in 52.5 ml of 95% alcohol and mixed with 47.5 ml of H_2O.

Procedure

A plastic cup was half filled with soil, and distilled water was added to more than saturate it. After the entire sample was wet more soil was added to make a mixture which was nearly solid but still showed some flow

characteristics and whose surface glistened. It was allowed to stand an hour and then checked again for saturation. The electrodes of a Corning pH meter were placed in the paste. The pH was read and recorded.

For the soluble salts determination, a DuoSeal Vac pump model 1402 with bell jars and Buchner funnels was used. About 30 saturated pastes were filtered through Buchner funnels at one time. Three or four ml of extract were obtained and run through a Conductivity Bridge model RC 16B2. Readings were recorded and rechecked by forcing the extract out and refilling again.

For each sample one ml of extract was transferred to a crucible and 24 ml of water were added to it. Then .5 ml of buffer solution, 3 drops of calmagite and 5 drops of methyl red solution were added. It was then titrated with .01-N CDTA, and the number of ml used recorded.

Phosphate Determination
(Murphy Rily Method)

Reagents

A. 12 gms of Ammonium Molybdate were dissolved in 250 ml of water, and .2908 gm of antimony potassium titrate was dissolved in 100 ml of water. Both of the dissolved reagents were added to 1 liter of $5NH_2SO_4$ (148 ml conc. H_2SO_4/L) and mixed thoroughly and brought to 2 liters with water. The reagent was stored in Pyrex bottle in a dark cool compartment.

B. 1.056 gm Ascorbic Acid were dissolved in 200 ml of Reagent A, mixed thoroughly and brought to 250 ml with water. The Reagent was used within 24 hours.

Procedure

Fifty grams of soil were put in a pint jar, and 250 ml of distilled water were added. The contents were mixed and attached to a gas distributing manifold. CO_2 was allowed to flow through the jar for 15 minutes. Each sample was then filtered. When sufficient clear extract had been collected 25 ml aliquots were transferred to 250 ml beakers and placed on hot plates to evaporate to dryness (to be used for nitrate determination). A 20 ml aliquot was placed in a 50 ml Ehrlenmeyer flask. (Water was added to make 20 ml when it became necessary to use a smaller aliquot). Five ml of reagent B were added and mixed in. Ten minutes were allowed for full color intensity to develop. Percent transmittance was read on Sepctronic 20 at 840 using a 1" viewing tube. (Calibration was made with plain water.) A chart was referred to for conversion to ppm in original sample.

Nitrate Determination

Reagents

A. Phenoldisulfonic acid (100 grams of pure white pherol crystals) warmed to liquify in a 400 ml beaker were slowly poured into 600 ml of H_2SO_4 in a 1500 ml Ehrlenmeyer flask. The sulfuric acid was kept in motion by swirling. 300 ml of fuming sulfuric acid (15-18% SO_3) were slowly added. It was mixed well and put on a hot plate for 2 hours at 100°C. A beaker was inverted over the flask. The reagent was kept in an amber colored bottle.

B. Ammonium hydroxide - con. (28%)

Procedure

When the samples which had been set to evaporate during the phosphate determination had dried and cooled, 2 ml of phenoldisulfonic acid were added; making sure to bring in contact with the dry reaction. Twenty ml of water were added and mixed by swirling. Then 6-7 ml of concentrated ammonium hydroxide were added. When cool, it was made up to 50 ml volume with water. The mixture was then poured into a viewing tube and transmittance was read on the Spectronic 20. (A blank made to the same volume from distilled water and reagent used was used to set the instrument on 100). The corresponding ppm were read from a curve made from standard solutions. Multiplication by any dilution factors used was made when necessary.

Organic Carbon Determination

Reagents

A. 1N potassium dicromate (49.04 gms $K_2Cr_2O_7$ to 1 liter solution).

B. Concentrated sulfuric acid.

C. .5-N ferrous sulfate (140 gms of $FeSO_4.7H_2O$ to 1 liter solution).

D. Silver sulfate (powder).

Procedure

Organic matter was determined on disturbed samples by the dichromate method. Thirty organic samples were weighed out at the same time that texture samples were taken. Two gram samples were taken for soils at an 0-3" level and four gram ones for all other levels. Twenty ml of 1N potassium dichromate were added with a pipet to the soil, then 20 ml of

concentrated sulfuir acid were added. The samples were allowed to stand for an hour after which half a gram of silver sulfate and 100 ml of distilled water were added. They were then filtered through a Buchner funnel with four 25 ml aliquots of distilled water. Next a .5-N ferrous sulfate solution was standardized by titrating into a similar mixture excepting the soil. Then each sample was titrated (a new standardization was made after every tenth sample). The dry weight was calculated from the percentage moisture of the texture samples, and organic matter from dry weight, ferrous sulfate used and ferrous sulfate calibrated.

SECTION 3

SOIL PROFILE DESCRIPTIONS

by

John A. Williams

Watershed 3

The profiles are all representative of the Springerville soils with color hues ranging from 10YR to 7.5YR. This range in hues is characteristic of the Springerville soils and illustrates the gray brown to reddish brown colors that are normal for the series.

You will note that profile 24 is calcareous to the surface. Profile 16 is representative of the Springerville soils we have named as "Channery."

Watershed 6

The profiles are representative of three soil series: Gem, Siesta, and Springerville. The following list shows the arry of profiles by series:

Gem	Gem (red)	Siesta	Springerville
Pit 12	Pit 75	Pit 130	Pit 17
" 35	" 118		" 21
" 65			" 41
" 83			
" 91			
" 98			
" 106			
" 128			

Two profiles, Nos. 75 and 118, are labeled "Gem (red)" because of the distinct reddish brown colors of the subsoils. These are Gem profiles that appear to have an influence from reddish brown colored parent materials.

Pit 3-6, Map Unit 322

Surface: 10% gravel
40% stone
15% cobble

Horizon

A-- 0-2"-Brown (10YR 5/3) stony clay loam, dark brown (10YR 4/3) moist; (weak very fine granular) structure; slightly hard, friable, sticky and plastic; noneffervescent, neutral (pH 7.2); clear smooth boundary.

C1--2-8"-Dark brown (10YR 4/3) clay, dark brown (10YR 4/3) clay, dark brown (10YR 4/3) moist; massive; very hard, very firm, sticky and plastic; noneffervescent mildly alkaline (pH 7.4); clear wavy boundary.

C2--8-12"-Dark gray brown (10YR 4/2) clay, very dark gray brown (10YR 3/2) moist; massive with prominent slickensides; very hard, very firm, very sticky and very plastic; noneffervescent mildly alkaline (pH 7.4); clear wavy boundary.

C2--8-12"+-Dark gray brown (10YR 4/2) clay, very dark gray brown (10YR 3/2) moist; massive with prominent slickensides; very hard, very firm, very sticky and very plastic; noneffervescent mildly alkaline (pH 7.6).

Pit 3-10, Map Unit 322

Surface: 35% gravel
20% cobble
10% stone

Horizon

A1--0-2"-Light brown (7.5YR 6/4) clay, brown (7.5YR 5/4) moist; weak very fine granular; slightly hard, very friable, slightly sticky and slightly plastic; noneffervescent; neutral (pH 7.2); clear smooth boundary; gravel 5%.

C1--2-12"-Brown (7.5YR 5/4) clay, dark brown (7.5YR 4/2) moist; common slickensides on structureless massive bodies; very hard, very firm, very sticky and very plastic; strongly effervescent; mildly alkaline (pH 7.6); clear wavy boundary; gravel 5%.

C2--12-26"-Brown (7.5YR 5/4) clay, dark brown (7.5 YR 4/2) moist; common slickensides on structureless massive bodies; very hard, very firm, very sticky and very plastic; violently effervescent; moderately alkaline (pH 8.4); gravel 5%.

Pit 3-16, Map Unit 322

Surface: 70% gravel
15% cobble

Horizon

A--0-2"-Dark gray brown (10YR 4/2) very gravelly clay, very dark gray brown (10YR 3/2) moist; weak very fine granular structure; soft, very friable, sticky and plastic; noneffervescent, neutral (pH 7.2); clear smooth boundary.

C1--2-8"-Very dark gray brown (10YR 3/2) clay, same color moist; massive with common distinct slickensides; hard, firm, very sticky and very plastic; noneffervescent, mildly alkaline (pH 7.4); clear wavy boundary.

C2--8-12"+-Color, texture, and structure same as horizon above; very hard, very firm, very sticky and very plastic; noneffervescent, mildly alkaline (pH 7.4).

C2--8-12"+-Color, texture, and structure same as horizon above; very hard, very firm, very sticky and very plastic; noneffervescent, mildly alkaline (pH 7.4).

Pit 3-24, Map Unit 322

Surface: 40% gravel
20% cobble
30% stone

Horizon

A--0-3"-Brown (7.5YR 4/2) very gravelly clay, cark brown (7.5YR 3/2) moist; weak very fine granular structure; slightly hard, friable, sticky and plastic; effervescent, mildly alkaline (pH 7.8); clear smooth boundary.

C1--3-13"-Gravelly clay, same color as horizon above; massive with common distinct slickensides; hard, firm, sticky and plastic; effervescent, moderately alkaline (pH 8.2); clear wavy boundary.

C2--13-23"-Very dark gray brown (10YR 3/2) clay, same color moist; massive with common distinct slickensides; very hard, very firm, very sticky and very plastic; strongly effervescent, moderately alkaline (pH 8.4).

Pit 3-40, Map Unit 322

Surface: 80% gravel
10% stone

Horizon

A1--0-2"-Reddish brown (5YR 5/3) gravelly clay, dark reddish brown (5YR 3/2) moist; weak very fine and fine granular structure; slightly hard, friable, slightly sticky and plastic; noneffervescent; neutral (pH 7.2); clear smooth boundary; 15% gravel and 2% stone.

C1--2-12"-Dark reddish gray (5YR 4/2) clay, dark reddish brown (5YR 3/3) moist; slickensides are common on massive structureless bodies; hard, firm, sticky and plastic; noneffervescent; mildly alkaline (pH 7.4); clear wavy boundary; 10% gravel and 2% stone.

C2--12-27"+-Dark reddish brown (5YR 3/3) gravelly clay, dark reddish brown (5YR 2/2) moist; slickensides are common on massive structureless bodies; very hard, very firm, very sticky and plastic; noneffervescent; mildly alkaline (pH 7.8); 25% gravel.

Pit 3-44, Map Unit 322

Surface: 50% gravel
10% cobble
20% stone

Horizon

A1--0-2"-Brown (7.5YR 5/4) clay loam, dark brown (7.5YR 4/4) moist; weak very fine granular; slightly hard, very friable, slightly sticky and slightly plastic; noneffervescent; neutral (pH 7.2); clear smooth boundary; gravel 5%, stone 2%.

C1--2-14"-Dark brown (7.5YR 4/2) clay, dark brown (7.5YR 3/2) moist; common slickensides on structureless massive bodies; hard, firm, sticky and plastic; slightly effervescent; mildly alkaline (pH 7.6); clear wavy boundary; gravel 5%, stone 2%.

C2--12-25"+-Dark brown (7.5YR 4/2) clay, dark brown (7.5YR 3/2) moist; common slickensides on structureless massive bodies; very hard, very firm, very sticky and very plastic; strongly effervescent; moderately alkaline (pH 8.2); gravel 5%.

Pit 3-49, Map Unit 322

Surface: 65% gravel
10% cobble
5% stone

Horizon

A--0-2"-Light brown (7.5YR 6/4) very gravelly clay, brown (7.5YR 5/4) moist; weak very fine and fine granular structure; slightly hard, friable, sticky and plastic; noneffervescent neutral (pH 7.2); clear smooth boundary.

C1--2-12"-Dark brown (10YR 4/3) clay, same color moist; massive with common slickensides on masses; hard, firm, very sticky and very plastic; noneffervescent mildly alkaline, (pH 7.4); clear wavy boundary.

C2--12-25"+-Color and texture same as horizon above; massive with distinct slickensides on faces of large aggregates; very hard, very firm, very sticky and very plastic; noneffervescent, (pH 7.4).

Pit 3-86, Map Unit 322

Surface: 40% gravel
25% cobble
10% stone

Horizon

A1--0-2"-Reddish brown (5YR 5/3) gravelly clay, reddish brown (5YR 4/3) moist; weak fine granular structure; slightly hard, firm, sticky and plastic; noneffervescent, neutral (pH 7.2) clear smooth boundary; 10% gravel and 2% cobble.

C1--2-12"-Reddish brown (5YR 4/3) clay, dark reddish brown (5YR 3/3) moist; slickensides are common massive structureless bodies; hard, firm, sticky and plastic; noneffervescent; mildly alkaline (pH 7.4); clear wavy boundary; 5% gravel and 2% cobble.

C2--12-24+"-Reddish brown (5YR 4/3) clay dark reddish brown (5YR 4/3) clay dark reddish brown (5YR 3/3) moist; slickensides are common on massive structureless bodies; very hard, very firm, very sticky and plastic; noneffervescent; mildly alkaline (pH 7.4); 5% gravel and 2% cobble.

Pit 3-88, Map Unit 322

Surface: gravel 35%
stone 20%
cobble 15%

A1--0-2"-Light brown (7.5YR 6/4) clay, dark brown (7.5YR 4/2) moist; weak fine platy and weak very fine granular structure; slightly hard, very friable, slightly sticky and slightly plastic; noneffervescent; neutral (pH 7.2); clear smooth boundary; gravel 5%, stone 2%.

C1--2-12"-Dark brown (7.5YR 4/2) clay, dark brown (7.5YR 3/2) moist; common slickensides on structureless massive bodies; hard, firm sticky and plastic; noneffervescent; mildly alkaline (pH 7.4); clear wavy boundary; gravel 5%, stone 2%.

C2--12-22+"-Dark brown (7.5YR 4/2) clay, dark brown (7.5YR 3/2) moist; common slickensides on structureless bodies; very hard, very firm, very sticky and very plastic; slightly effervescent; moderately alkaline (pH 8.0); gravel 5%, stone 2%.

Pit 3-90, Map Unit 322

Surface: 35% gravel
15% cobble
10% stone

Horizon

A1--0-2"-Light brown (7.5YR 6/4) clay brown (7.5YR 5/4) moist; weak very fine granular structure; slightly hard, very friable, slightly sticky and plastic; noneffervescent; mildly alkaline (pH 7.4); clear smooth boundary; 5% gravel and 2% cobble.

C1--2-13"-Dark brown (7.5YR 4/2) clay dark brown (7.5YR 3/2) moist; slickensides are common on massive structureless bodies; hard, firm, sticky and plastic; weakly effervescent; mildly alkaline (pH 7.8); clear wavy boundary; 5% gravel.

C2--13-27"-Brown (7.5YR 4/2) clay dark brown (7.5YR 3/2) moist; slickensides are common on massive structureless bodies; very hard; very firm, very sticky and very plastic; strongly effervescent; moderately alkaline (pH 8.4); 5% gravel.

Pit 3-103, Map Unit 322

Surface: 40% gravel
10% cobble
15% stone

Horizon

A--0-2"-Dark gray brown (10YR 4/2) gravelly clay, very dark gray brown (10YR 3/2) moist; weak very fine granular structure; slightly hard, friable, sticky and plastic; noneffervescent, neutral (pH 7.2); clear smooth boundary.

C1--2-13"- Very dark gray brown (10YR 3/3) clay, same color moist; massive with common distinct slickensides; very hard, very firm, very sticky and very plastic; noneffervescent, mildly alkaline (pH 7.4).

Pit 3-108, Map Unit 322

Surface: 15% gravel
5% cobble
20% stone

Horizon

A--0-3"-Brown (7.5YR 5/4) stony clay, dark brown (7.5YR 4/4) moist; weak very fine granular structure; slightly hard, very friable, sticky and plastic; slightly effervescent, moderately alkaline (pH 8.0); clear smooth boundary.

C1--3-12"-Brown (7.5YR 4/2) clay, dark brown (7.5YR 3/2) moist; massive with common distinct slickensides; slightly hard, friable, sticky and plastic; noneffervescent mildly alkaline (pH 7.4); clear wavy boundary.

C2--12-21+"-Color, texture, and structure same as horizon above; very hard, very firm, very sticky and very plastic; noneffervescent, mildly alkaline (pH 7.4).

Pit 3-115, Map Unit 322

Surface: 75% gravel
5% cobble

Horizon

A1--0-3"-Reddish brown (5YR 5/3) very gravelly clay reddish brown (5YR 4/3) moist; weak very fine granular structure; slightly hard, friable, sticky and plastic; noneffervescent; neutral (pH 7.2); clear smooth boundary; 35% gravel.

C1--3-12"-Dark reddish brown (5YR 3/2) clay dark reddish brown (5YR 2/2) moist; slickensides are common on massive structureless bodies; hard, firm, sticky and plastic; noneffervescent; mildly alkaline (pH 7.4); clear wavy boundary; 10% gravel and 10% cobble.

C2--12-23+"-Reddish brown (2.5YR 4/4) cobbly clay dark reddish brown (2.5YR 3/4) moist; slickensides are common on massive structureless bodies; very hard, very firm, very sticky and plastic; noneffervescent; mildlu alkaline (pH 7.4); clear wavy boundary; 2% gravel and 15% cobble.

Pit 3-119, Map Unit 322

Surface: 10% cobble
80% gravel

Horizon

A1--0-2"-Dark brown (7.5YR 4/2) gravelly clay, dark brown (7.5YR 3/2) moist; weak very fine granular structure; slightly hard, friable, slightly sticky and slightly plastic; noneffervescent; neutral (pH 7.2); clear smooth boundary; gravel 15%.

C1--2-11"-Dark brown (7.5YR 4/2) clay, dark brown (7.5YR 3/2) moist; massive; hard, firm sticky and plastic; noneffervescent; mildly alkaline (pH 7.4); clear wavy boundary, gravel 5%.

C2--11-24"-Reddish brown (5YR 4/4) clay, dark reddish brown (5YR 3/3) moist; common slickensides on structureless massive boddies; very hard, very firm, very sticky and very plastic; slightly effervescent; mildly alkaline (pH 7.4); clear wavy boundary; gravel 10%.

C3--24-43"-+Reddish brown (5YR 4/4) clay, dark reddish brown (5YR 3/4) moist; common slickensides on structureless massive bodies; extremely hard, extremely firm, very sticky and very plastic; strongly effervescent; moderately alkaline (pH 8.2); gravel 5%.

Pit 6-12, Map Unit 323

Horizon

A1--0-2"-Brown (7.5YR 5/2) gravelly clay, loam, dark brown (7.5YR 4/2) moist; moderate medium platy and moderate fine granular structure; slightly hard, friable, slightly sticky and slightly plastic; noneffervescent; neutral (pH 7.2), clear smooth boundary. Gravel 40%, cobble 5%.

B21--2-9"-Brown (7.5YR 5/2) clay, dark brown (7.5YR 4/2) moist;weak fine and medium subangular blocky structure; hard, firm, sticky and plastic; noneffervescent; mildly alkaline (pH 7.4); clear wavy boundary. Gravel 5%, stone 5%.

B22t--9-16"-Dark brown (7.5YR 4/2) clay, dark brown (7.5YR 3/2) moist; strong coarse angular and subangular blocky structure; very hard, very firm, very sticky and very plastic; few moderately thick clay films on ped faces; noneffervescent; mildly alkaline (pH 7.4); clear wavy boundary. Gravel 10%, stone 5%.

C1--16-20+"-Dark reddish gray (5YR 4/2) clay, reddish brown (5YR 5/3) moist; common slickensides border structureless, massive bodies ; very hard, very firm, very sticky and very plastic; noneffervescent mildly alkaline (pH 7.6). Gravel 10%, stone 5%.

Pit 6-17, Map Unit 323

Horizon

A1--0-2"-Weak red (10YR 5/2) cobbly clay, weak red (10YR 4/2) moist; moderate very fine and fine granular structure; slightly hard, very friable, sticky and plastic; noneffervescent; neutral (pH 7.2); clear wavy boundary. Gravel 5%, cobble 20%.

C1--2-21"-Brown (7.5YR 4/2) clay, dark brown (7.5YR 3/2) moist; massive; very hard, very firm, very sticky and very plastic; mildly alkaline (pH 7.4); clear wavy boundary. Gravel 10%.

C2--21-36+-Dark reddish gray (5YR 4/2) clay, dark reddish brown (5YR 3/3) moist; common slickensides border structureless; massive bodies; very hard, very firm, very sticky and very plastic; few fine white lime concretions; mildly alkaline (pH 7.8). Gravel 5%.

Pit 6-21, Map Unit 322

Horizon

A1--0-3"-Weak red (10YR 5/2) cobbly clay, weak red (10YR 4/2) moist; weak coarse granular structure; hard, firm, sticky and plastic; noneffervescent; neutral (pH 7.2); clear smooth boundary. Gravel 20%, cobble 25%.

C1--3-12"-Brown (7.5YR 5/2) clay, dark brown (7.5YR 4/2) moist; common slickensides border structureless massive bodies; very hard, very firm, very stocky and very plastic; noneffervescent; mildly alkaline (pH 7.4); clear wavy boundary. Gravel 5%, stone 2%.

C2--12-22+"-Brown (7.5YR 5/4) clay, dark brown (7.5YR 4/2) moist; common slickensides border structureless massive bodies; very hard, very firm, very sticky and very plastic; noneffervescent; mildly alkaline (pH 7.8); Gravel 10%, cobble 5%, stone 2%.

Pit 6-35, Map Unit 322

Horizon

A1--0-2"-Brown (7.5YR 5/2) cobbly clay loam, dark brown (7.5YR 4/2) moist; weak fine subangular blocky structure; slightly hard, very friable, slightly sticky and slightly plastic; noneffervescent; neutral (pH 7.2); clear smooth boundary. Gravel 10%, cobble 20%.

B21t--2-10"-Dark reddish gray (YR 4/2) clay, dark reddish brown (5YR 3/2) moist; moderate medium and coarse subangular blocky structure; hard, firm, sticky and plastic; common thin clay films in pores and few thin clay films on ped faces; noneffervescent; mildly alkaline (pH 7.4); clear wavy boundary. Gravel 5%.

B22t--10-20"-Reddish brown (5YR 5/4) clay, reddish brown (5YR 4/4) moist; moderate medium and coarse subangular blocky structure; very hard, very firm, very sticky and very plastic; common thin clay films in pores and few thin clay films on ped faces; noneffervescent; mildly alkaline (pH 7.4); abrupt wavy boundary; Gravel 5%.

C1--20-35+"-Brown (7.5YR 5/4) clay, darkbbrown (7.5YR 4/4) moist; few slickensides on structureless massive bodies; very hard, very firm, very sticky and very plastic; few thin clay films on ped faces; very slightly effervescent; midly alkaline (pH 7.8). Gravel 5%.

Pit 6-41, Map Unit 322

Horizon

A1--0-3"-Brown (7.5YR 5/2) gravelly clay loam, dark brown (7.5YR 4/2); weak fine platy structure; slightly hard, very friable, slightly sticky and slightly plastic; noneffervescent; neutral (pH 7.2); clear smooth boundary. Gravel 35%, cobble 10%.

C1--3-9"-Reddish brown (5YR 4/3) clay, dark reddish brown (5YR 3/4) moist; massive; hard, firm, sticky and plastic; few thin clay films in pores; noneffervescent; mildly alkaline (pH 7.4) clear wavy boundary. Gravel 5%, cobble 2%.

C2--9-21"-Reddish brown (5YR 4/4) clay, dark reddish brown (5YR 3/4); massive; very hard, very firm, very sticky and very plastic; noneffervescent; mildly alkaline (pH 7.6); clear wavy boundary. Gravel 5%, cobble 2%.

C3--21-40"-Reddish brown (5YR 4/4) clay, dark reddish brown (5YR 3/4) moist; massive, very hard, very firm, very sticky and very plastic; slightly effervescent; moderately alkaline (pH 8.2). Common carbonates and common slickensides. Gravel 5%, cobble 2%, stone 3%.

Pit 6-65, Map Unit 322

Horizon

A1--0-3"-weak red (10YR 5/3) cobbly clay loam, dusky red (10YR 3/3); moderate very fine and fine granular structure; slightly hard, very friable, slightly sticky and slightly plastic; noneffervescent; neutral (pH 7.2); clear smooth boundary. Gravel 10%, cobble 15%.

B21--3-11"-Brown (7.5YR 5/4) clay, dark brown (7.5YR 4/4) moist; moderate medium subangular blocky; hard, firm, sticky and plastic; noneffervescent; mildly alkaline (pH 7.4); clear wavy boundary. Gravel 5%, cobble 5%.

B225--1-34"-Brown (7.5YR 5/4) clay, dark brown (7.5YR 4/4) moist; strong medium and coarse angular and subangular blocky structure; very hard, very firm, very sticky and very plastic; common moderately thick clay films on ped faces; noneffervescent; mildly alkaline (pH 7.6); abrupt wavy boundary. Gravel 2%.

C1--34-43+"-Dark brown (5YR 4/4) clay, dark brown (5YR 4/4) moist; commons; slickensides border structureless massive bodies; very hard, very firm, very sticky and very plastic; slightly effervescent; moderately alkaline (pH 8.0). Gravel 2%, cobble 2%.

Pit 6-75, Map Unit 323

Horizon

Surface coarse fragments - Gravel 20%, cobble 10%.

A1--0-2"-Brown (10YR 5/3) gravelly clay loam, dark brown (10YR 4/3) moist; moderate fine and medium granular structure; slightly hard, very friable, slightly sticky and slightly plastic; noneffervescent; neutral (pH 7.2); clear smooth boundary. Gravel 20%, 10% cobble.

B2t--2-11"-Dark reddish gray (5YR 4/2) clay reddish brown (5YR 3/2) moist; moderate fine and medium subangular blocky structure; hard, firm, sticky and plastic; common thin clay films in pores; noneffervescent mildly alkaline (pH 7.4); clear wavy boundary. Gravel 10%.

B22t--11-24"-Reddish brown (5YR 5/3) clay, reddish brown (5YR 4/3) moist; strong medium subangular blocky structure; very hard, very firm, very sticky and very plastic; common thin clay films in pores, few thin clay films on peds; noneffervescent; mildly alkaline (pH 7.4); clear wavy boundary. Gravel 5%.

B23t--24-37+"-Reddish brown (5YR 5/4) clay, reddish brown (5YR 4/4) moist; strong fine and medium angular and subangular blocky structure; very hard, very firm, very sticky and very plastic; common moderately thick clay films on ped faces; noneffervescent; mildly alkaline (pH 7.8). Gravel 10%.

Pit 6-88, Map Unit 323

Horizon

A1--0-3"-Grayish brown (10YR 5/2) very dark grayish-brown (10YR 3/2) moist; gravelly clay loam, moderate very fine and fine granular structure; slightly hard, very friable, slightly sticky and plastic; noneffervescent; neutral (pH 7.2) clear smooth boundary. 35% gravel, 10% cobble.

B2t--3-13"-Brown (7.5YR 4/2) clay dark brown (7.5YR 3/2) moist; moderate coarse and very coarse angular blocky and subangular blocky structure; hard, firm, sticky and plastic, few moderately thick clay films on pores and ped faces; noneffervescent; mildly alkaline (pH 7.4); clear wavy boundary; 5% gravel.

B3--13-22"-Brown (7.5YR 4/2) clay dark brown (7.5YR 3/2) moist; massive; very hard, very firm, very sticky and plastic; slickensides noneffervescent; mildly alkaline (pH 7.4); clear wavy boundary; 5% gravel.

C--22-28"-Reddish brown (5YR 4/4) gravelly clay, dark reddish brown (5YR 3/4) moist; massive; very hard, very firm, very sticky and plastic; slickensides noneffervescent; mildly alkaline (pH 7.8); 25% gravel.

Pit 6-91, Map Unit 323

Horizon

A1--0-2"-Brown (10YR 5/3) clay loam, dark brown (10YR 3/3) moist; moderately fine platy and very fine granular structure; slightly hard, friable, slightly sticky and plastic; noneffervescent; neutral (pH 7.2); clear, smooth boundary; 5% gravel.

B2t--2-18"-Brown (7.5YR 5/2) clay dark brown (7.5YR 4/2) moist; strong medium and coarse subangular and angular blocky structure; very hard, very firm, very sticky and plastic; common moderately thick clay films on ped faces; noneffervescent; mildly alkaline (pH 7.4); clear wavy boundary; 5% gravel.

B3--18-27"-Brown (7.5YR 4/2) clay dark brown (7.5YR 3/2) moist; massive; very hard, very firm, very sticky and plastic; many slickensides; noneffervescent; mildly alkaline (pH 7.4); abrupt wavy boundary; 5% gravel.

C--27-35"-Reddish brown (5YR 5/4) very gravelly clay dark reddish brown (5YR 3/4) moist; massive; very hard, very firm, very sticky and plastic; many slickensides; noneffervescent; mildly alkaline (pH 7.6); 35% cobble. Surface has 35% gravel, 10% cobble.

Pit 6-98, Map Unit 323

Horizon

A1--0-3"-Brown (10YR 5/3) gravelly clay dark brown (10YR 3/3) moist; weak and moderate very fine granular structure; slightly hard, very friable, slightly sticky and plastic; noneffervescent; neutral (pH 7.2); clear smooth boundary; 35% gravel.

B21t--3-12"-Brown (7.5YR 5/4) clay dark brown (7.5YR 4/4) moist; moderate coarse and very coarse subangular blocky structure; hard, firm, sticky and plastic; few thin clay films on pores; noneffervescent; mildly alkaline (pH 7.4) clear wavy boundary; 5% gravel.

B22t--12-24"-Brown (7.5YR 4/2) clay dark brown (7.5YR 3/2) moist; moderate coarse subangular and angular blocky structure; very hard, very firm, very sticky and plastic; few moderately thick clay films on ped faces; noneffervescent; mildly alkaline (pH 7.6); 5% gravel and 2% cobble.

Pit 6-106, Map Unit 323

Horizon

A1--0-2"-Brown (7.5YR 5/2) gravelly clay loam, dark brown (7.5YR 4/2) moist; moderate very fine and fine granular structure; slightly hard, very friable, slightly sticky and plastic; noneffervescent; neutral (pH 7.2); clear smooth boundary; 35% gravel, 15% cobble.

B21t--2-13"-Brown (7.5YR 4/2) clay dark brown (7.5YR 3/2) moist; moderate coarse angular and subangular blocky structure; hard, firm, sticky and plastic; noneffervescent; mildly alkaline (pH 7.4); clear wavy boundary; 5% gravel.

B22t--13-25"-Brown (7.5YR 5/2) clay dark brown (7.5YR 4/2) moist; moderate medium and coarse subangular blocky structure; very hard, very firm, very sticky and plastic, common thin clay films on ped faces; noneffervescent; mildly alkaline (pH 7.6); 10% gravel.

Pit 6-118, Map Unit 323

Horizon

A1--0-3"-Brown (7.5YR 5/2) gravelly clay loam, dark brown (7.5YR 4/2) moist; weak fine platy and moderate fine granular structure; slightly hard, very friable, slightly sticky and plastic; noneffervescent; neutral (pH 7.2); abrupt smooth boundary; 15% gravel, 10% cobble.

B21t--3-9"-Reddish brown (5YR 4/3) clay dark reddish brown (5YR 3/4) moist; moderate medium subangular blocky structure; hard, firm, sticky and plastic; few thin clay films on pores; noneffervescent; mildly alkaline (pH 7.4) clear wavy boundary; 5% gravel.

B22t--9-22"-Reddish brown (5YR 4/4) clay dark reddish brown (5YR 3/4) moist; moderate medium subangular blocky structure; very hard, firm, sticky and plastic; common moderately thick clay films on ped faces; noneffervescent; mildly alkaline (pH 7.4); abrupt wavy boundary; 5% gravel.

B23t--22-33"-Reddish brown (5YR 4/4) clay dark reddish brown (5YR 3/4) moist; weak medium and coarse subangular blocky structure; very hard, firm, sticky and plastic; weakly effervescent; 10% gravel, 15% cobble.

Pit 6-128, Map Unit 322

Horizon

A1--0-3"-Pale brown (10YR 6/3) clay loam, brown (10YR 5/3) moist; moderate very fine and fine granular structure; slightly hard, very friable, slightly sticky and plastic; noneffervescent; neutral (pH 7.2); clear smooth boundary; 5% gravel, 5% cobble.

B21t--3-13"-Grayish brown (10YR 5/2) clay dark grayish brown (10YR 4/2) moist; moderate medium subangular blocky structure; hard, firm sticky and plastic; few thin clay films on pores; noneffervescent; neutral (pH 7.3) clear wavy boundary; 5% gravel.

B22t--13-26"-Very dark grayish brown (10YR 3/2) clay, very dark brown (10YR 2/2) moist; strong fine and medium subangular and angular blocky structure; very hard, firm sticky and plastic; moderate thin clay films on pores; noneffervescent; neutral (pH 7.3); clear wavy boundary; 10% gravel and 2% stone.

B3t--26-31"-Light brown (7.5YR 6/4) gravelly clay brown (7.5YR 5/4) moist; moderate medium subangular blocky structure; very hard, firm, sticky and plastic; common thin clay films on pores; noneffervescent; mildly alkaline (pH 7.4); abrupt wavy boundary; 25% gravel and 5% cobble.

C--31-46"-Reddish brown (5YR 5/4) clay reddish brown (5YR 4/4) moist; massive; very hard, firm sticky and plastic; common slickensides; weakly effervescent in spots; mildly alkaline (pH 7.6); 10% gravel and 2% cobble.

Pit 6-130, Map Unit 392

Horizon

A1--0-2"-Reddish gray (5YR 5/2) gravelly silt loam, dark reddish gray (5YR 4/2) moist;moderate medium platy and moderate fine granular structure; slightly hard, very friable, slightly sticky and plastic, noneffervescent; neutral (pH 7.0); clear smooth boundary; 60% gravel, 30% cobble.

B21t--2-12"-Reddish brown (5YR 4/3) clay dark reddish brown (5YR 3/3) moist; moderate medium subangular structure; hard, firm, sticky and plastic; common moderately thick clay films on pores; noneffervescent; neutral (pH 7.2); clear wavy boundary; 10% gravel and 10% cobble.

B22t--12-22"-Reddish brown (5YR 4/3) clay dark reddish brown (5YR 3/4) moist; strong medium and coarse angular blocky structure; very hard, very firm, very sticky and plastic; common moderately thick clay films on ped faces and pores; noneffervescent; mildly alkaline (pH 7.4); 5% gravel and 10% cobble.

Watershed 9

Because many of the pits contained greatly similar profiles, the pits have been grouped and one profile is given for 2, 3, or 4 pits. In most cases the differences between profiles of the pits as grouped consist of slight changes in thickness of the horizons or minor changes in color. The textures, structure, consistence, etc. are identical for the grouped profiles. The reporting scheme is outlined as follows:

Pits in Map Unit 362

Group 1 — Profile 9-21 reported

Pit No.	21	22	118
Horizon			
A1	0-3"	0-2"	0-3"
B21t	3-8"	2-10"	3-9"
B22t	8-15"	10-18"	9-18"

Group 2 — Profile 9-26 reported

Pit No.	23	26	29
Horizon			
A1	0-3"	0-3"	0-2"
B21t	3-9"	3-16"	2-11"
B22t	9-25"	16-30"	11-25"

Group 3 — Profile 9-30 reported

Group 4 — Profile 9-60 reported

Pit No.	36	60	62	63
Horizon				
A1	0-3"	0-4"	0-4"	0-4"
B21t	3-11"	4-11"	4-14"	4-19"
B22t	11-20"	11-30"	14-30"	19-30"

Group 5 Profile 9-70 reported

Pit No.	70	90	113
A1	0-3"	0-3"	0-3"
B21t	3-10"	3-11"	3-11"
B22t	10-20"	11-20"	11-22"

Group 6 Profile 9-115 reported

Pit No.	115	117
Horizon		
A1	0-3"	0-2"
B2t	3-16"	2-22"
B3	16-34"	22-26"

Pits in Map Unit 362B

Profile 9-105 reported

Pits in Map Unit 364

Profile 9-91 reported

Pits in Map Unit 394

Profiles 9-83 and 9-121 reported

Pits in Map Unit 300C

Group 1 Profile 9-33 reported

Pit No.	33	120
Horizon		
A1	0-3"	0-3"
B21t	3-10"	3-13"
B22t	10-17"	13-20"
R	17-20+"	20-28+"

Group 2 Profile 9-49 reported

Pit No.	49	96
Horizon		
A1	0-4"	0-2"
B21t	4-14"	2-13"
B22t	14-30"	13-16+"

Pits in Map Unit 352

Pit No.	32	97	102	103	104
Horizon					
A1	0-2"	0-4"	0-5"	0-2"	0-3"
B21t	2-10"	4-16"	5-13"	2-9"	3-9"
B22t	10-23"	16-25"	13-16"	9-24"	9-23"

Pits in Map Unit 352A

Profiles 9-18 and 9-56 reported

Pit No.	18	56	57
Horizon			
A1	0-4"	0-2"	0-3"
B21t	4-12"	2-11"	3-11"
B22t	12-15"	11-50"	11-35"
R	15-20+"	50+"	35+"

Pits in Map Unit 392

Group 1 Profile 9-13 reported

Pit No.	10	13	47
Horizon			
A1	0-3"	0-3"	0-3"
B21t	3-11"	3-13"	3-10"
B22t	11-33+"	13-29+"	10-32"
B3	-	-	32-72+"

Group 2 Profiles 9-81, 9-83, and 9-85 reported

Pit No.	81	83	85	101	110
Horizon					
A1	0-4"	0-3"	0-3"	0-2"	0-2"
B21t	4-19"	3-12"	3-13"	2-14"	2-11"
B22t	19-30"	12-28"	13-20"	14-21"	11-16"
B23t	-	-	20-30"	21-38	-

Pits in Map Unit 392A

Profile 9-55 reported

Pits in Map Unit 392B

Profiles 9-14 and 9-80 reported

Pits in Map Unit 354

Profile 9-68 reported

Pit 9-13, Map Unit 392

Surface: gravel 35%
cobble 10%

Horizon

O1--1-0"-Decomposed and partially decomposed pine needles.

A1--0-3"-Dark reddish gray (5YR 4/2) gravelly clay loam, dark reddish brown (5YR 3/2) moist; moderate fine and very fine granular structure; slightly hard, friable, slightly and slightly plastic; noneffervescent; neutral (pH 6.9); clear smooth boundary. Gravel 25%, cobble 5%.

B21t--3-13"-Weak red (2.5YR 4/2) clay, dusky red (2.5YR 3/2) moist; moderate fine and medium subangular blocky structure; hard, firm, sticky and plastic; common thin clay films in pores and on ped faces; noneffervescent; neutral (pH 7.3); clear smooth boundary. Gravel 15%.

B22t--13-29"+-Dark reddish brown (2.5YR 2/4) very gravelly clay, dark reddish brown (2.5YR 3/4) moist; moderate fine and medium angular and subangular blocky structure; hard, firm, sticky and plastic; noneffervescent; neutral (pH 7.3). Gravel 35%.

Pit 9-14, Map Unit 392B

On 10% slope with NW aspect.

Horizon

A1--0-4"-Dark grayish brown (10YR 4/2) very gravelly clay loam, dark grayish brown (10YR 3/2) moist; moderate very fine granular structure; slightly hard, very friable, slightly sticky and plastic; noneffervescent; neutral (pH 6.7); clear smooth boundary; 35% gravel and 10% cobble.

B21t--4-16"-Reddish brown (5YR 5/4) very gravelly clay, reddish brown (5YR 4/4) moist; weak fine and medium angular and subangular blocky structure; hard, friable, sticky and plastic; few thin clay films on pores and ped faces; noneffervescent; neutral (pH 7.1); clear wavy boundary; 35% gravel.

B3--16-34"-Yellowish red (5YR 5/6) very gravelly clay, yellowish red (5YR 4/6) moist; common medium slickensides; hard, firm, very sticky and very plastic; noneffervescent; neutral (pH 7.1); 40% gravel and 10% cobble.

Pit 9-18, Map Unit 352

On 18% slope with SE aspect.

Horizon

A1--0-4"-Reddish brown (5YR 4/3) gravelly clay loam, dark reddish brown (5YR 3/3) moist; moderate fine and medium granular and subangular blocky structure; slightly hard, very friable, slightly sticky and plastic; noneffervescent; neutral (pH 6.8) clear smooth boundary; 15% gravel.

B21t--4-12"-Dark reddish brown (5YR 3/2) clay, dark reddish brown (5YR 2/2) moist; moderate fine and medium subangular blocky structure; hard, friable, sticky and plastic; few thin clay films on pores; few thin clay films on pores; noneffervescent; neutral (pH 7.2); clear wavy boundary; 10% gravel.

B22t--12-15"-Dark reddish gray (5YR 4/2) clay, dark reddish brown (5YR 3/2) moist; strong fine and medium subangular and angular blocky structure; hard, firm, sticky and plastic; common moderately thick clay films on pores and ped faces; noneffervescent; neutral (pH 7.2) gravel 10%.

R--15-20"+-Reddish yellow (5YR 6/8) consolidated cinders, yellowish red (5YR 5/8) moist.

Pit 9-21, Map Unit 362

Horizon

A1--0-3"-Brown (7.5YR 4/2) clay loam, dark brown (7.5YR 3/2) moist; weak fine platy structure; slightly hard, very friable, slightly sticky and plastic; noneffervescent; neutral (pH 7.2); clear smooth boundary; 5% gravel and 5% cobble.

B21t--3-8"-Brown (7.5YR 4/2) clay, dark brown (7.5YR 3/2) moist; weak medium and coarse subangular blocky structure; hard, firm, sticky and plastic; few thin clay films on pores; noneffervescent; mildly alkaline (pH 7.4); clear wavy boundary; 5% gravel and 5% cobble.

B22t--8-15"+-Brown (7.5YR 4/2) cobbly clay, dark brown (7.5YR 3/2) moist; strong medium angular and subangular blocky structure;hard, firm, sticky, and plastic; few thin clay films on pores; noneffervescent; mildly alkaline (pH 7.4); 5% gravel, 15% cobble and 10% stone.

Pit 9-26, Map Unit 362

On 7% slope with NW aspect

Horizon

A1--0-3"-Dark grayish brown (10YR 4/2) clay loam, very dark grayish (10YR 3/2) moist; weak fine and medium platy structure; hard, very friable, slightly sticky and slightly plastic; noneffervescent; neutral (pH 6.9); clear smooth boundary; 5% gravel and 2% cobble.

B21t--3-16"-Dark reddish brown (5YR 3/2) clay, dark reddish brown (5YR 2/2) moist; strong fine and medium angular and subangular blocky structure; hard, friable, sticky and plastic; common thin clay films on pores; noneffervescent; neutral (pH 7.1); gradual wavy boundary; 10% gravel.

B22t--16-30+"-Brown (7.5YR 4/2) gravelly cobbly clay, dark brown (7.5YR 3/2) moist; strong coarse angular and subangular blocky structure; very hard, film, sticky and plastic; many thick clay films on ped faces; noneffervescent; neutral (pH 7.1); 15% gravel and 15% cobble.

Pit 9-30, Map Unit 362

On 2% slope with NW aspect.

Horizon

A1--0-4"-Dark grayish brown (10YR 4/2) clay loam, very dark grayish brown (10YR 3/2) moist; moderate fine platy and granular structure; slightly hard, very friable, slightly sticky and slightly plastic; noneffervescent; neutral (pH 6.9); clear smooth boundary; 5% gravel and 10% cobble.

B21t--4-12"-Dark reddish gray (5YR 4/2) clay, dark reddish brown (5YR 3/2) moist; moderate fine and medium subangular blocky structure; hard, firm, sticky and plastic; common thin clay films on pores; noneffervescent; neutral (pH 7.3); clear wavy boundary; 10% gravel.

B22t--12-21"-Reddish brown (5YR 4/4) gravelly clay, dark reddish brown (5YR 3/4) moist; strong medium angular blocky structure; very hard, very firm, very sticky and very plastic; many moderately thin clay films on ped faces; noneffervescent; mildly alkaline (pH 7.4); 15% gravel.

Pit 9-32, Map Unit 352

On 6% with S aspect

Horizon

A1--0-2"-Brown (7.5YR 4/2) gravelly clay loam, dark brown (7.5YR 3/2) moist; moderate medium platy structure; slightly hard, very friable, slightly sticky and plastic; noneffervescent; neutral (pH 6.9); clear smooth boundary; 15% gravel.

B21t--2-10"-Reddish gray (5YR 5/2) clay, dark reddish gray (5YR 4/2) moist; moderate fine and medium subangular blocky structure; hard, friable, sticky and plastic; few thin clay films on pores; noneffervescent; neutral (pH 7.3); clear wavy boundary; 10% gravel.

B22t--10-23"-Reddish brown (5YR 4/3) clay, dark reddish brown (5YR 3/3) moist; strong fine and medium angular and subangular blocky structure; very hard, very firm, very sticky and very plastic; common moderately thick clay films on ped faces; noneffervescent; neutral (pH 7.3) 10% gravel.

Pit 9-33, Map Unit 300C

On 15% slope with NW aspect.

Horizon

A1--0-3"-Brown (7.5YR 4/2) clay loam, dark brown (7.5YR 3.2) moist; moderate medium platy structure; slightly hard, very friable, slightly sticky and slightly plastic; noneffervescent; neutral (pH 6.9); clear smooth boundary; 10% gravel.

B21t--3-10"-Dark reddish gray (5YR 4/2) clay, dark reddish brown (5YR 3/2) moist; moderate medium subangular blocky structure; hard, friable, sticky and plastic; few thin clay films on pores; noneffervescent; neutral (pH 7.3); clear wavy boundary; 10% gravel.

B22t--10-17"-Reddish brown (5YR 4/3) gravelly clay, dark reddish brown (5YR 3/3) moist; moderate coarse angular and subangular blocky structure; very hard, firm, sticky and plastic; few thin clay films on pores; noneffervescent; neutral (pH 7.3) abrupt wavy boundary, 15% gravel.

R--17-20+"-Reddish brown (2.5YR 4/4) partially decomposed cinders, dark reddish brown (2.5YR 3/4) moist.

Pit 9-49, Map Unit 300C

On 6% slope with NW aspect.

Horizon

A1--0-4"-Very dark grayish brown (10YR 3/2) clay, very dark brown (10YR 2/2) moist; weak fine and medium subangular blocky structure; hard, friable, sticky and plastic; noneffervescent; neutral (pH 6.8); 10% gravel.

B21t--4-14"-Brown (7.5YR 4/2) clay, dark brown (7.5YR 3/2) moist; moderate medium subangular blocky structure; hard, friable, sticky and plastic; few thin clay films on pores; noneffervescent; neutral (pH 7.1); 5% gravel and 2% cobble.

B22t--14-30"-Brown (7.5 YR 5/4) clay, dark brown (7.5YR 4/4) moist; strong medium and coarse angular and subangular blocky structure; hard, firm, sticky and plastic; many moderately thick clay films on ped faces; noneffervescent; neutral (pH 7.1); 5% gravel and 2% cobble.

Pit 9-55, Map Unit 392A

On 16% slope with NW aspect.

Horizon

A1--0-3"-Dark reddish gray (5YR 4/2) gravelly clay loam, dark reddish brown (5YR 3/2) mosit; weak very fine and fine granular structure; slightly hard, very friable, slightly sticky and plastic; noneffervescent; neutral (pH 6.9); abrupt smooth boundary; 25% gravel.

B21--3-12"-Reddish brown (2.5YR 5/4) clay loam, reddish brown (2.5YR 4.4) moist; moderate very fine and fine subangular blocky structure; slightly hard, very friable, sticky and plastic; noneffervescent; neutral (pH 7.2); clear wavy boundary; 10% gravel.

B22t--12-32"-Weak red (10YR 4/4) gravelly clay loam (10YR 3.4) moist; stong medium angular and subangular blocky structure; hard, friable, sticky and plastic; few moderately thick clay films on pores and ped faces; noneffervescent; neutral (pH 7.2); 15% gravel and 5% cobble.

Pit 9-56, Map Unit 352

On 20% slope with W aspect.

Horizon

A1--0-2"-Reddish brown (2.5YR 4/4) clay loam, dark reddish brown (2.5YR 3/4) moist; weak fine and medium granular and subangular blocky structure; hard, very friable, slightly sticky and slightly plastic; noneffervescent; neutral (pH 6.8); abrupt smooth boundary; 10% gravel and 5% cobble.

B21t--2-11"-Weak red (10R 4/4) clay, dusky red (10R 3/4) moist; moderate medium subangular blocks structure; hard, friable, sticky and plastic; few thin clay films on pores; noneffervescent; neutral (pH 7.0); clear smooth boundary; 10% gravel and 10% cobble.

B22t--11-50"-Reddish brown (2.5YR 4/4) clay, dark reddish brown (2.4YR 3/4) moist; moderate fine and medium subangular blocky structure; hard, firm, sticky and plastic; few thin clay films on ped faces; noneffervescent; neutral (pH 7.0); 10% gravel and 10% cobble.

R--50"+-Cinders

Pit 9-60, Map Unit 362

On 3% slope with NE aspect.

Horizon

A1--0-4"-Brown (7.5YR 5/4) clay loam, dark brown (7.5YR 4/4) moist; weak very fine and fine subangular blocky structure; slightly hard, very friable, slightly sticky and slightly plastic; noneffervescent; neutral (pH 7.3); clear smooth boundary; 10% gravel and 10% cobble.

B21t--4-11"-Reddish brown (5YR 4/3) clay, dark reddish brown (5YR 3/3) mosit; moderate fine and medium subangular blocky structure; hard, friable, sticky and plastic; few thin clay films on ped faces; noneffervescent; mildly alka;ine (pH 7.4); clear wavy boundary; 10% gravel and 15% cobble.

B22t--11-30"-Reddish brown (5YR 5/4) clay, reddish brown (5YR 4/4) moist; moderate medium angular and subangular blocky structure; hard, friable, sticky and plastic; many moderately thick clay films on ped faces; noneffervescent; mildly alkaline; 5% gravel and 10% cobble.

Pit 9-68, Map Unit 354

Surface: 10% gravel

Horizon:

A1--0-1"-Grayish brown (10YR 5/2) clay, dark grayish brown (10YR 4/2) moist; moderate medium platy and moderate fine granular structure; slightly hard, very friable, slightly sticky and pl stic; non-effervescent; neutral (pH 6.9); clear smooth boundary; 5% gravel and 2% cobble.

B21t--1-8"-Very dark gray (5YR 3/1) clay block (5YR 2/1) moist; moderate medium subangular blocky structure; hard, friable, sticky and plastic; few thin clay films on pores; noneffervescent; neutral (pH 7.3); clear wavy boundary; 5% gravel and 2% cobble.

B22t--8-20"-Brown (7.5YR 4/2) clay dark brown (7.5YR 3/2) moist; moderate coarse and very coarse subangular and angular blocky structure; very hard, very firm, very sticky and plastic; many thick clay films on ped faces; noneffervescent; neutral (pH 7.3); 5% gravel and 2% cobble.

Pit 9-70, Map Unit 362

Horizon

A1--0-3"-Dark grayish brown (10YR 4/2) clay, very dark grayish brown (10YR 3.2) moist; weak medium subangular blocky structure; hard, friable, sticky and plastic; noneffervescent; neutral (pH 6.9) clear smooth boundary; 5% gravel.

B21t--3-10"-Very dark grayish brown (10YR 3/2) clay, very dark brown (10YR 2/2) moist; moderate medium subangular blocky structure; hard, firm sticky and plastic; common thin clay films on ped faces; noneffervescent; neutral (pH 7.3); clear wavy boundary; 10% gravel and 5% cobble.

B22t--10-20"-Brown (7.5YR 4/2) clay, dark brown (7.5YR 3.2) moist; strong coarse and very coarse subangular blocky structure; very hard, very firm, very sticky and very plastic; many thick clay films on ped faces; noneffervescent; neutral (pH 7.3); 10% gravel and 5% cobble.

Pit 9-80, Map Unit 392B

Surface: gravel 12%
cobble 10%
stone 2%

Horizon

A1--0-3"-Very dark grayish brown (10YR 3/2) gravelly clay loam; very dark brown (10YR 2/2) moist; moderate fine and medium granular structure; slightly hard, very friable, slightly sticky and slightly plastic; noneffervescent; neutral (pH 6.8); clear smooth boundary; gravel 15%.

B21t--3-12"-Dark brown (7.5YR 4/2) clay, dark brown (7.5YR 3/2) moist; moderate fine and medium subangular blocky structure; hard, friable, sticky and plastic; few thin clay films in pores; noneffervescent; neutral (pH 7.2); clear wavy boundary gravel 10%.

B22t--12-23+"-Dark reddish brown (5YR 3/3) very gravelly clay, dark reddish brown (5YR 2/2) moist with common mottling of reddish yellow (7.5YR 6/8), strong brown (7.5YR 5/8) moist; strong medium angular and subangular blocky structure; hard, firm, very sticky and very plastic; common thin clay films in pores and on ped faces; noneffervescent; neutral (pH 7.2); gravel 35%.

Pit 9-81, Map Unit 392

On 20% slope with SE aspect.

Horizon

A1--0-4"-Brown (7.5YR 4/2) clay loam, dark brown (7.5YR 3.2) moist; weak very fine and fine granular structure; slightly hard, very friable, slightly sticky and plastic; noneffervescent; neutral (pH 6.9); clear smooth boundary; 10% gravel.

B21t--4-19"-Dark reddish gray (5YR 4/2) clay, dark reddish brown (5YR 3/2) moist; moderate fine and medium subangular blocky structure; hard, friable, sticky and plastic; few thin clay films on pores; noneffervescent; neutral (pH 7.3); clear wavy boundary; 10% gravel.

B22t--19-30"-Yellowish red (5YR 5/8) very gravelly clay, yelbwish red (5YR 5/8) moist; moderate coarse subangular blocky structure; hard, firm, sticky and plastic; noneffervescent; neutral (pH 7.3); 35% gravel and 2% cobble.

Pit 9-83, Map Unit 392

Surface: gravel 20%

Horizon

A1--0-3"-Dark reddish gray (5YR 4/2) clay loam, dark reddish brown (5YR 3/2) moist; weak fine and medium subangular blocky structure; slightly hard, very friable, sticky and plastic; noneffervescent; neutral (pH 6.9); abrupt smooth boundary; gravel 5%, cobble 5%.

B21t--3-12"-Dark reddish gray (5YR 4/2) clay, dark reddish brown (5YR 3/2) moist; moderate medium subangular blocky structure; hard, friable, sticky and plastic; few thin clay films in pores; noneffervescent; mildly alkaline (pH 7.4); abrupt wavy boundary; gravel 5%, cobble 2%.

B22t--12-28"+-Reddish brown (5YR 4/4) clay, dark reddish brown (5YR 3/4) moist; moderate medium and coarse angular and subangular blocky structure, many thick clay films on ped faces; noneffervescent; mildly alkaline (pH 7.4); gravel 5%.

Pit 9-83, Map Unit 394

On 5% slope with SE aspect.

Horizon

A1--0-3"-Dark reddish gray (5YR 4/2) clay loam, dark reddish brown (5YR 3/2) moist; weak fine and medium subangular blocky structure; slightly hard, very friable, sticky and plastic; noneffervescent; neutral (pH 6.9); abrupt smooth boundary; 5% gravel and 5% cobble.

B21t--3-12"-Weak red (2.5YR 4/2) clay, dusky red (2.5YR 3/2) moist; moderate medium subangular blocky structure; hard, friable, sticky and plastic; noneffervescent; mildly alkaline (pH 7.4: abrupt smooth boundary; 5% gravel and 2% cobble.

B22t--12-28"+-Reddish brown (5YR 4/4) clay, dark reddish brown (5YR 3/4) moist; strong medium and coarse angular and subangular blocky structure; very hard, very firm, very sticky and very plastic; many thick clay films on ped faces; noneffervescent; mildly alkaline (pH 7.4); 5% gravel.

Pit 9-85, Map Unit 392

On 6% slope with N aspect.

Horizon

A1--0-3"-Brown (7.5YR 4/2) clay loam, dark brown (7.5YR 3/2) moist; weak fine and medium subangular blocky structure; slightly hard, friable, slightly sticky and plastic; noneffervescent; neutral (pH 6.9); clear smooth boundary; 5% gravel and 2% cobble.

B21t--3-13"-Reddish brown (5YR 4/3) clay, dark reddish brown (5YR 3/3) moist; moderate fine and medium subangular blocky structure; hard, firm, sticky and plastic; few thin clay films on pores; noneffervescent; neutral (pH 7.2); clear wavy boundary; 5% gravel and 2% cobble.

B22t--13-20"-Dark reddish gray (5YR 4/2) clay, dark reddish brown (5YR 3/2) moist; strong coarse angular and subangular blocky structure; hard, firm, sticky and plastic; common moderately thick clay films on ped faces; noneffervescent; neutral (pH 7.2); clear wavy boundary, 5% gravel.

B23t--20-30"-Reddish brown (5YR 4/3) very gravelly clay, dark reddish brown (5YR 3/3) moist; moderate coarse subangular blocky structure; hard, firm, very sticky and very plastic; common moderately thick clay films on ped faces and pores; noneffervescent; neutral (pH 7.3); 35% gravel.

Pit 9-91, Map Unit 364

On 4% slope with NW aspect.

Horizon

A1--0-1"-Brown (10YR 5/3) clay loam, brown (10YR 4/3) moist; weak medium platy structure; slightly hard, very friable, slightly sticky and slightly plastic; noneffervescent; neutral (pH 7.2) abrupt smooth boundary; 5% gravel and 5% cobble.

B21t--1-8+"-Dark reddish gray (5YR 4/2) clay, dark reddish brown (5YR 3/2) moist; strong medium angular and subangular blocky structure; hard, friable, sticky and plastic; few thin clay films on pores; noneffervescent; neutral (pH 7.3);

8"+ large basalt stones under second Horizon with soil between stones.

Pit 9-85, Map Unit 392

On 6% slope with N aspect.

Horizon

A1--0-3"-Brown (7.5YR 4/2) clay loam, dark brown (7.5YR 3/2) moist; weak fine and medium subangular blocky structure; slightly hard, friable, slightly sticky and plastic; noneffervescent; neutral (pH 6.9); clear smooth boundary; 5% gravel and 2% cobble.

B21t--3-13"-Reddish brown (5YR 4/3) clay, dark reddish brown (5YR 3/3) moist; moderate fine and medium subangular blocky structure; hard, firm, sticky and plastic; few thin clay films on pores; noneffervescent; neutral (pH 7.2); clear wavy boundary; 5% gravel and 2% cobble.

B22t--13-20"-Dark reddish gray (5YR 4/2) clay, dark reddish brown (5YR 3/2) moist; strong coarse angular and subangular blocky structure; hard, firm, sticky and plastic; common moderately thick clay films on ped faces; noneffervescent; neutral (pH 7.2); clear wavy boundary, 5% gravel.

B23t--20-30"-Reddish brown (5YR 4/3) very gravelly clay, dark reddish brown (5YR 3/3) moist; moderate coarse subangular blocky structure; hard, firm, very sticky and very plastic; common moderately thick clay films on ped faces and pores; noneffervescent; neutral (pH 7.3); 35% gravel.

Pit 9-91, Map Unit 364

On 4% slope with NW aspect.

Horizon

A1--0-1"-Brown (10YR 5/3) clay loam, brown (10YR 4/3) moist; weak medium platy structure; slightly hard, very friable, slightly sticky and slightly plastic; noneffervescent; neutral (pH 7.2) abrupt smooth boundary; 5% gravel and 5% cobble.

B21t--1-8+"-Dark reddish gray (5YR 4/2) clay, dark reddish brown (5YR 3/2) moist; strong medium angular and subangular blocky structure; hard, friable, sticky and plastic; few thin clay films on pores; noneffervescent; neutral (pH 7.3);

8"+ large basalt stones under second Horizon with soil between stones.

Pit 9-97, Map Unit 352

WS #9

Surface: 35% gravel
5% cobble

Horizon:

A1--0-4"-Dark brown (7.5YR 4/2) gravelly clay loam, dark brown (7.5YR 3/2) moist; moderate very fine and fine granular structure; slightly hard, very friable, slightly sticky and plastic; noneffervescent; neutral (pH 6.9); abrupt smooth boundary; 15% gravel and 10% cobble.

B21t--4-16"-Dark reddish gray (5YR 4/2) gravelly cobbly clay dark reddish brown (5YR 3/2) moist; moderate medium subangular blocky structure; hard, firm, sticky and plastic, few thin clay films on pores; noneffervescent; neutral (pH 7.3); clear wavy boundary; 25% gravel and 15% cobble.

B22t--16-25"-Reddish brown (5YR 4/4) gravelly cobbly clay dark reddish brown (5YR 3/4) moist; moderate coarse angular blocky structure; very hard, very firm, very sticky and plastic; common moderately thick clay films on ped faces; noneffervescent; neutral (pH 7.3); 20% gravel and 25% cobble.

Pit 9-105, Map Unit 362B

On 25% slope with SE aspect.

Horizon

A1--0-4"-Reddish gray (5YR 5/2) clay, dark reddish gray (5YR 4/2) moist; weak medium subangular blocky structure; hard, friable, sticky and plastic; noneffervescent; neutral (pH 6.8); clear smooth boundary; clear smooth boundary; 5% gravel, 5% cobble, and 2% stone.

B22t--4-18"-Dark reddish gray (5YR 4/2) gravelly clay, dark reddish brown (5YR 3/2) moist; moderate medium subangular blocky structure; hard, firm, sticky and plastic; few thin clay films on pores; non-effervescent; neutral (pH 7.2); clear wavy boundary; 15% gravel and 2% cobble.

B23--18-38"-Dark reddish brown (5YR 3/2) very gravelly clay, dark reddish brown (5YR 2/2) moist; moderate medium angular and subangular blocky structure; hard, firm, sticky and plastic; noneffervescent; neutral (pH 7.2); 35% gravel, 10% cobble, and 10% stone.

Pit 9-115, Map Unit 362

On 13% slope with NW aspect.

Horizon

A1--0-3"-Brown (7.5YR 5/4) clay loam, dark brown (7.5YR 4/4) moist; strong fine and medium platy structure; slightly hard, very friable, slightly sticky and slightly plastic; noneffervescent; neutral (pH 7.0); clear smooth boundary; 5% gravel and 5% cobble.

B2t--3-16"-Reddish brown (5YR 4/3) clay, dark reddish brown (5YR 3/3) moist; moderate fine and medium angular and subangular blocky structure; hard, firm, sticky and plastic; few thin clay films on pores; noneffervescent; neutral (pH 7.2) clear wavy boundary; 5% gravel and 5% cobble.

B3--16-344"-Brown (7.5YR 4/2) gravelly clay, dark brown (7.5YR 3/2) moist; massive; very hard, very firm, very sticky and very plastic; noneffervescent; neutral (pH 7.2); 15% gravel and 10% cobble.

Pit 9-121, Map Unit 394

On 3% slope with SW aspect.

Horizon

A1--0-2"-Pinkish gray (5YR 6/2) clay loam, reddish gray (5YR 5/2) moist; moderate fine and medium granular structure; slightly hard, very friable, slightly sticky and slightly plastic; noneffervescent; neutral (pH 6.9); clear smooth boundary; 5% gravel.

B21t--2-15"-Reddish brown (5YR 5/3) clay, reddish brown (5YR 4/3) moist; moderate fine and medium subangular blocky structure; hard, firm, sticky and plastic; few thin clay films on pores; noneffervescent; neutral (pH 7.3); clear wavy boundary; 5% gravel.

B22t--15-24"-Reddish brown (25YR 4/4) clay, dark reddish brown (25YR 3/4) moist; strong medium and coarse angular blocky structure; very hard, very firm, very sticky and very plastic; many moderately thick clay films on ped faces; noneffervescent; neutral (pH 7.3); clear wavy boundary; 5% gravel.

B23t--24-35"-Reddish brown (5YR 5/4) very gravelly clay, reddish brown (5YR 4/4) moist; very hard, very firm, very sticky and very plastic; many moderately thick clay films on ped faces; noneffervescent; neutral (pH 7.3); 40% gravel.

Watershed II

Within the various mapping units there is considerable uniformity of the profiles, thus representative profiles are given for groups of 2, 3, or 4 pits. The grouping of the test pits according to mapping units is as follows:

Pits in Mapping Unit 323

Group I — Profile II-67 reported

Test pit Horizon	67	81	90
A	0-4"	0-4"	0-4"
B21t	4-12"	4-11"	4-12"
B22t	12-24+"	11-28+"	12-25"

Group 2 — Profile II-134 reported

Test Pit Horizon	27	41	76	134
A	0-2"	0-3"	0-2"	0-2"
B21t	2-12"	3-10"	2-8"	2-11"
B22t	12-32"	10-23"	8-22"	11-22"

Group 3 — Profile II-125 reported

Test pit Horizon	95	125
A	0-6"	0-5"
B21t	6-14"	5-13"
B22t	14-20"	13-20"

Group 4 — Profile II-61 reported and represents a deep pit with 5 horizons in the profile.

For Group 1: The profiles are most uniform in depth breaks, texture, structure and color. For each of the three profiles the first and second layers have 10YR hues while the third layer is 7.5YR.

The Group 2: Profiles are alike and this group represents those with thin surface layers. In all the profiles, the colors are on 10YR hue.

Group 3 Profiles represent that part of the 323 mapping unit with relatively thick surface layers (5-6").

The lone 11-61 profile is from a deep pit and the profile is distinctly representative of the 323 soils.

Pits in Mapping Unit 362

Group 1 Profile 11-29 reported.

Test Pit Horizon	29	131
A	0-2"	0-2"
B21t	2-10"	2-9"
B22t	10-28"	9-27"

These profiles represent a thin surface layer over a 25 to 26" well structured clay B1.

Group 2 Profiles 11-43 and 11-45 reported.

Test Pit Horizon	43	45
A	0-2"	0'2"
Test Pit Horizon	43	45
B2t	2-10"	2-8"
C	10-30"	8-37"

The two profiles become massive below 8 or 10 inch depth.

Group 3 Profile 11-17 reported as is the only one in the group. This profile has a thick (6") surface layer with a B1 transition horizon stop the well structured clay B2t horizon.

Pits in mapping unit 362A

Group 1 Profile 11-117 reported

Test Pit HOrizon	87	117	121
A	0-4"	0-4"	0-6"
B21t	4-19"	4-15"	6-15"
B22t	19-34"	15-30"	15-29"

Group 2 Profile 11-21 reported.

This profile has a thick (8)" surface layer atop 24" of clay Bt horizon.

Group 3 Profile 11-85 reported.

This profile grades to massive C horizon materials at 22".

Pit 11-17, Map Unit 323

Horizon

A1--0-6"-Dark grayish brown (10YR 4/2) clay loam, very dark grayish brown (10YR 3/2) moist; moderate fine and medium subangular blocky structure; hard, friable, sticky and plastic; noneffervescent; neutral (pH 7.1); clear wavy boundary; 5% gravel.

B1--6-13"-Brown (7.5YR 5/4) clay, dark brown (7.5YR 4/4) moist; strong medium subangular and angular blocky structure; very hard, very firm, very sticky and very plastic; noneffervescent; neutral (pH 7.3); gradual wavy boundary; 5% gravel.

B21t--13-19"-Brown (7.5YR 5/4) clay, dark brown (7.5YR 4/4) moist; strong medium and coarse angular blocky structure; extremely hard and firm, very sticky and plastic; many moderately thick clay films (pH 7.3); clear wavy boundary; 5% gravel.

B22t--19-32"-Dark brown (7.5YR 4/2) clay, dark brown (7.5YR 3/2) moist; strong coarse angular blocky structure; extremely hard and firm, very sticky and plastic; many thick clay films on ped faces; noneffervescent; neutral (pH 7.3); 5% gravel.

Pit 11-21, Map Unit 362A

On 10% slope with SW aspect.

Surface: 25% gravel
10% cobble

Horizon

A1--0-8"-Dark grayish brown (10YR 4/2) clay loam, very dark grayish brown (10YR 3/2) moist; moderate fine and medium subangular blocky structure; hard, friable, sticky and plastic; noneffervescent; neutral (pH 7.1); clear wavy boundary; gravel 5%.

B21t--8-15"-Brown (7.5YR 5/4) clay, dark brown (7.5YR 4/4) moist; strong medium angular and subangular blocky structure; very hard, very firm, very sticky and very plastic; noneffervescent; neutral (pH 7.4); gradual wavy boundary; gravel 5%.

B22t--15-23"-Brown (7.5YR 5/4) clay, dark brown (7.5YR 4/4) moist; strong medium and coarse angular blocky structure; extremely hard, extremely firm, very sticky and very plastic; many moderately thick clay films on ped faces; noneffervescent; neutral (pH 7.3); clear wavy boundary; gravel 5%.

B23t--23-32+"-Dark brown (7.5YR 4/2) clay, dark brown (7.5YR 3/2) moist; strong medium and coarse angular blocky structure; extremely hard, extremely firm, very sticky and very plastic; many thick clay films on ped faces; noneffervescent; neutral (pH 7.3); gravel 5%.

Pit 11-29, Map Unit 362

On 5% slope with W aspect.

Horizon

A1--0-2"-Grayish brown (10YR 5/2) clay loam, dark grayish brown (10YR 4/2) moist; weak fine and medium platy structure; slightly hard, very friable, sticky, and plastic; noneffervescent; neutral (pH 7.2); clear smooth boundary; 5% gravel and 10% cobble.

B21--2-10"-Dark grayish brown (10YR 4/2) clay, very dark grayish brown (10YR 3/2) moist; moderate fine and medium subangular blocky structure; hard, firm, sticky and plastic; noneffervescent; mildly alkaline (pH 7.4); abrupt wavy boundary; 5% gravel, 10% cobble, and 5% stone.

B22t--10-28"-Brown (7.5YR 5/4) clay, dark brown (7.5YR 4/4) moist; strong medium and coarse subangular and angular blocky structure; very hard, very firm, sticky and plastic; common thin clay films on ped faces; noneffervescent; mildly alkaline (pH 7.4); 5% gravel, 10% cobble, and 5% stone.

Pit 11-43, Map Unit 362

On 2% slope with SW aspect.

Horizon

A1--0-2"-Grayish brown (10YR 5/2) clay, very dark grayish brown (10YR 3/2) moist; weak medium subangular blocky structure; hard, firm, sticky and plastic; neutral (pH 7.2); clear smooth boundary; 5% gravel and 10% cobble.

B21t--2-10"-Dark grayish brown (10YR 4/2) clay, very dark grayish brown (10YR 3/2) moist; moderate medium subangular blocky structure; very hard, very firm, sticky and plastic; few thin clay films on pores, noneffervescent; mildly alkaline (pH 7.4); clear wavy boundary; 2% gravel, 2% stone, and 2% cobble.

C--10-30+"-Very dark grayish brown (10YR 3/2) clay, very dark brown (10YR 2/2) moist; massive; very hard, very firm, sticky and plastic; noneffervescent; mildly alkaline (pH 7.4); 2% gravel.

Pit 11-45, Map Unit 362

Surface: 35% gravel
5% cobble

A1--0-2"-Dark grayish brown (10YR 4/2) clay loam very dark grayish brown (10YR 3/2) moist; moderate very fine and fine granular structure; slightly hard, very friable, slightly sticky and plastic; noneffervescent; meutral (pH 7.2); clear wavy boundary; 5% gravel and 5% cobble.

C1--2-8"-Grayish brown (10YR 5/2) clay dark grayish brown (10YR 4/2) moist; slickensides are common on massive structureless bodies; hard, firm, sticky and plastic; noneffervescent; mildly alkaline (pH 7.4); clear wavy boundary; 5% gravel and 5% cobble.

C2--8-31+"-Brown (7.5YR 5/4) clay dark brown (7.5YR 4/4) moist; slickensides are common on massive structureless bodies; very hard, very firm, sticky and plastic; noneffervescent; mildly alkaline (pH 7.4); 5% gravel and 2% cobble.

Pit 11-61, Map Unit 323

Horizon

A1--0-3"-very dark gray (10YR 3/1) clay, black (10YR 2/1) moist; moderate fine and medium subangular blocky structure; hard, firm, very sticky and very plastic; noneffervescent; mildly alkaline (pH 7.5) clear smooth boundary; 5% gravel.

B21t--3-14"-Very dark grayish brown (10YR 3/2) clay, very dark brown (10YR 2/2) moist; strong medium and coarse angular and subangular blocky structure; very hard, very firm, very sticky and very plastic; common thick clay films on ped faces; noneffervescent; neutral (pH 7.3); clear smooth boundary; 2% gravel.

B22t--14-28"-Dark grayish brown (10YR 4/2) clay, very dark grayish brown (10YR 3/2) moist; strong coarse angular and subangular blocky structure; very hard, very firm, very sticky and very plastic; common thin clay films on ped faces; noneffervescent; neutral (pH 7.3) gradual wavy boundary; 2% gravel.

B23t--28-38"-Dark grayish brown (10YR 4/2) clay, very dark grayish brown (10YR 3/2) moist; strong coarse subangular and angular blocky structure; very hard, very firm, very sticky and very plastic; common moderately thick clay film on ped faces; noneffervescent; mildly alkaline (pH 7.8); clear wavy boundary; 2% gravel.

C--38-50+"-Brown (7.5YR 5/4) clay, dark brown (7.5YR 4/4) moist; massive; very hard, very firm, very sticky and very plastic; slight effervescence; moderately alkaline (pH 8.2); clear wavy boundary.

Pit 11-67, Map Unit 323

On 5% slope with S aspect

Surface: 20% gravel
10% stone
5% cobble

Horizon

A1--0-4"-Grayish brown (10YR 5/2) clay, dark grayish brown (10YR 4/2) moist; moderate medium subangular blocky structure; hard, friable, sticky and plastic; noneffevescent; neutral (pH 7.2); clear wavy boundary; gravel 10%.

B21t--4-12"-Dark grayish brown (10YR 4/2) clay, very dark grayish brown (10YR 3/2) moist; strong coarse angular and subangular blocky structure; extremely hard, very firm, very sticky and very plastic; common thin clay films on ped faces; noneffervescent; neutral (pH 7.2); clear wavy boundary; gravel 5%.

B22t--12-24+"-Dark brown (7.5YR 4/2) clay, dark brown (7.5YR 3/2) moist; strong medium and coarse angular and subangular blocky structure; extremely hard, very firm, very sticky and very plastic; many thin clay films on ped faces; noneffervescent; neutral (pH 7.2); gravel 5%, cobble 5%.

Pit 11-85, Map Unit 362A

Surface: 30% gravel
10% cobble
5% stone

Horizon

A--0-4"-Gray brown (10YR 5/2) loam, very dark gray brown (10YR 3/2) moist; weak fine subangular blocky structure; slightly hard, very friable, slightly sticky and slightly plastic; noneffervescent, neutral (pH 7.2); clear wavy boundary.

B21t--4-11"-Dark gray brown (10YR 4/2) clay, very dark gray brown (10YR 3/2) moist; moderate medium subangular blocky structure; hard, firm, sticky and plastic; 10% gravel and 10% cobble; noneffervescent, mildly alkaline (pH 7.4); abrupt wavy boundary.

B22t--11-22"-Color and texture same as horizon above; strong medium angular blocky structure; very hard, very firm, sticky and plastic; 5% gravel and 5% cobble; noneffervescent; mildly alkaline (pH 7.4); abrupt wavy boundary.

C--22-24+"-Brown (7.5YR 5/4) gravelly clay, dark brown (7.5YR 4/4) moist; massive; very hard, very firm, sticky and plastic; 20% gravel; effervescent, moderately alkaline (pH 8.2).

Pit 11-117, Map Unit 362A

Horizon

A1--0-4"-Dark gray (10YR 4/1) clay, very dark gray (10YR 3/1) moist; weak fine and medium subangular blocky structure; slightly hard, friable, sticky and plastic; noneffervescent; neutral (pH 7.2); clear wavy boundary; 2% gravel.

B21t--4-15"-Dark grayish brown (10YR 4/2) clay, very dark grayish brown (10YR 3/2) moist; moderate medium and coarse subangular blocky structure; very hard, very firm, very sticky and very plastic; few thin mildly alkaline (pH7.4); gradual wavy boundary; 2% gravel.

B22t--15-30+"-Dark grayish brown (10YR 4/2) clay, very dark grayish brown (10YR 3/2) moist; strong coarse subangular and angular blocky structure; very hard, very firm, very sticky and very plastic; common thin clay films on ped faces; noneffervescent; mildly alkaline (pH 7.4); 5% stone.

Pit 11-125, (WS #11), Map Unit 323

Surface: 25% gravel
10% cobble
10% stone

Horizon

A1--0-5"-Grayish brown (10YR 5/2) clay loam dary grayish brown (10YR 4/2) moist; moderate very fine and fine granular structure; hard, friable, sticky and plastic; noneffervescent; neutral (pH 7.2); abrupt smooth boundary; 10% gravel and 3% cobble.

B21t--5-13"-Brown (10YR 5/3) clay dark brown (10YR 4/3) moist; strong medium subangular blocky structure; extremely hard and firm, sticky and plastic; common thin clay films on ped facesl mildly alkaline (pH 7.4); noneffervescent; clear wavy boundary; 10% gravel and 5% cobble.

B22t-13-20+"-Brown (7.5YR 5/4) clay dark brown (7.5YR 4/4) moist; moderate medium and coarse angular blocky structure; very hard and firm, sticky and plastic; common moderately thick clay films on ped faces; noneffervescent; mildly alkaline (pH 7.4); 10% gravel and 5% cobble.

Pit 11-134, Map Unit 323

Horizon

A1--0-2"-Grayish brown (19YR 5/2) clay, very dark grayish brown (10YR 3/2) moist; weak fine and medium subangular blocky structure; hard, friable, sticky and plastic; noneffervescent; neutral (pH 7.2); clear wavy boundary; 5% gravel.

B21t--2-11"-Brown (10 YR 4/3) clay, dark brown (10YR 3/3) moist; moderate medium subangular and angular blocky structure; hard, firm, sticky and plastic; common moderately thick clay films on ped faces; noneffervescent; mildly alkaline (pH 7.4); gradual wavy boundary; 2% gravel.

B22t--11-22+"-Brown (10YR 4/3) clay, dark brown (10YR 3/3) moist; moderate coarse subangular and angular blocky structure; hard, firm sticky and plastic; common moderately thick clay films on ped faces; noneffervescent; mildly alkaline (pH 7.4); 2% gravel.

SECTION 4

ANALYSIS OF SOIL PROFILE DESCRIPTIONS

by

Rafaela M. Santa Cruz

Very often watershed management recommendations and practices are made on the basis of soil mapping units. Since mapping units are delineated principally from soil profile descriptions made in the field it was thought worthwhile to perform some simple non parametric tests on the qualitative description made of the 123 soil profiles identified in this study.

Chi square tests were made to determine differences in texture, structure, consistency, and color. These characteristics were ranked as follows:

Structure	Texture	Dry Consistency
1. Subangular blocky	1. Clay	1. Soft
2. Angular blocky	2. Clay loam	2. Slightly hard
3. Massive	3. Silty clay	3. Hard
4. Granular	4. Loam	4. Very hard
5. Platy	5. Silt loam	5. Extremely hard

Moist Consistency	Wet Consistency
1. Firm	1. Slightly sticky and slightly plastic
2. Very firm	2. Slightly sticky and plastic
3. Friable	3. Sticky and plastic
4. Very friable	4. Very sticky and very plastic
	5. Very sticky and plastic

Both dry and moist color descriptions were analyzed. All hues were different degrees of yellow (10 to 2.5). Values ranged from 2 to 6. Chroma values varied from 2 to 8.

Comparisons were made between the soil series found on the five watersheds of the study both including and excluding the Springerville soil series. Analyses were made for each of the first 3 soil horizons. Results are given in Tables 1 through 6.

In considering all soil series differences in structure were apparent in the 2nd and 3rd horizons but not in the 1st horizon. This was due to the essentially massive structure of the subsurface horizon of the Springerville soil. The square analysis included all series excepting Springerville showed no significant difference for any of the horizons. Soil texture differed somewhat among all series in the surface horizon, but did not differ at lower depths. Dry and moist consistency did not differ among the soil series in the first horizon, but did differ in the lower horizons. Differences in dry consistency were highly significant in the lower horizons for all soil series. Wet consistency differe somewhat in the up er horizon but was not significant in lower depths.

The hue of soil color differed significantly among the soil series in all 3 horizons for both dry and moist conditions. Value differed for the first horizon, in both wet and dry conditions and for the wet condition in the other horizons. It was not significantly different in the lower horizon for the wet condition. Chroma did not differ significantly for the wet or dry condition for the first 2 soil horizons.

The thickness of the soil horizons as described were remarkably uniform among the 5 series regardless of their classifications, as A, B_{22}, etc.

It appears that in considering soil profile descriptions per se only very slight differences exist between the 362, 352, 392, and 323 soil series; Series 322 being the exception.

No great differences were apparent in the pH values for any of the 3 horizons among all soil series.

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Table

Table 1. X^2 Test on Soil Profile Descriptions

	All Soil Series			Not Including Springerville Series		
First Horizon	X^2	DF		X^2	DF	
Struc	18.617	14	NS	7.456	11	NS
Tex	41.001	24	*	33.942	19	*
Dry	22.016	14	NS	12.085	7	NS
Moist	13.611	14	NS	12.824	11	NS
Wet	30.604	19	*	27.875	15	*
Second Horizon						
Struc	108.766	14	**	9.038	11	NS
Tex	8.322	9	NS	6.740	7	NS
Dry	39.262	19	**	35.165	15	**
Moist	28.256	14	*	22.563	11	*
Wet	15.184	14	NS	11.647	11	NS
Third Horizon						
Struc	50.241	14	**	3.049	11	NS
Tex	7.828	9	NS	6.323	7	NS
Dry	40.098	14	**	27.546	11	**
Moist	28.325	14	*	19.656	11	NS
Wet	14.910	14	NS	6.458	11	NS

NS = Non-significant
* = Significant
** = Highly significant

Table 2. X^2 Test on Color Descriptions

	All Soil Series			Not Including Springerville Series		
First Horizon	X^2	DF		X^2	DF	
Hue (dry)	43.227	24	**	39.70	19	**
Value "	58.60	19	**	30.699	11	**
Chroma"	24.83	19	NS	20.948	15	NS
Hue (moist)	39.254	19	**	36.166	15	**
Value "	29.128	14	*	20.556	11	*
Chroma "	15.679	19	NS	11.915	15	NS
Second Horizon						
Hue (dry)	58.199	19	**	45.792	15	**
Value "	13.02	14	NS	12.338	11	NS
Chroma "	3.702	14	NS	3.352	11	NS
Hue (moist)	63.015	19	**	45.792	15	**
Value "	89.202	19	**	74.676	15	**
Chroma "	2.624	14	NS	2.456	11	NS
Third Horizon						
Hue (dry)	41.741	19	**	39.978	15	**
Value "	29.269	19	NS	24.767	15	NS
Chroma "	39.992	24	*	33.272	19	*
Hue (moist)	44.272	19	**	39.978	15	**
Value "	36.295	19	**	37.253	15	**
Chroma "	35.326	19	*	25.608	15	*

NS = Non significant
* = Significant
** = Highly significant

Table 3. MEAN DEPTH OF HORIZONS FROM SOIL PROFILE DESCRIPTIONS

First Horizon

Series	$\bar{X}$	$S_{\bar{x}}$	.05 limits	.01 limits
322	2.37	.11	2.1 - 2.6	2.0 - 2.7
323	3.00	.28	2.4 - 3.6	2.2 - 3.8
352	3.12	.40	2.2 - 4.1	1.7 - 4.5
362	3.11	.16	2.8 - 3.4	2.7 - 3.5
392	2.92	.19	2.5 - 3.3	2.3 - 3.5

Second Horizon

Series	$\bar{X}$	$S_{\bar{x}}$	.05 limits	.01 limits
322	9.16	.39	8.3 - 10.0	8.0 - 10.3
323	9.39	.79	7.7 - 11.0	7.1 - 11.7
352	8.25	.62	6.8 - 9.7	6.1 - 10.4
362	8.33	.38	7.6 - 9.1	7.4 - 9.3
392	10.0	.62	8.6 - 11.4	8.1 - 11.9

Third Horizon

Series	$\bar{X}$	$S_{\bar{x}}$	.05 limits	.01 limits
322	11.1	1.06	8.9 - 13.3	8.0 - 14.2
323	11.5	.70	10.0 - 13.0	9.5 - 13.5
352	15.0	4.20	5.1 - 24.9	0.3 - 29.7
362	11.90	.72	10.5 - 13.3	10.1 - 13.7
392	13.75	1.74	9.9 - 17.6	8.3 - 19.2

Table 4. PIT DEPTH

Watershed #3

Sample Point Number	Depth in inches	Sample Point Number	Depth in inches	Sample Point Number	Depth in inches
88	36	24	23	10	36
49	45	108	29	6	18
40	15	86	24	90	36
119	15	16	12	44	40
115	20	103	18		

Watershed #6

Sample Point Number	Depth in inches	Sample Point Number	Depth in inches	Sample Point Number	Depth in inches
130	23	21	30	17	48
41	48	26	36	92	42
118	33	35	48	88	34
128	58	106	33	82	50
75	51	98	31		
65	48	12	30		

Table 4 (Cont'd). Watershed #9

Sample Point Number	Depth in inches	Sample Point Number	Depth in inches	Sample Point Number	Depth in inches
62	31	80	30	42	49
63	36	83	24	90	18
60	37	85	32	52	18
56	48	49	42	16	22
55	33	47	87	91	9
23	28	46	12	124	24
22	21	13	37	121	35
21	21	14	29	120	32
113	21	105	41	96	15
115	32	75	38	97	26
117	31	36	15	33	23
118	21	104	6	32	22
26	30	103	21	30	43
57	48	102	17	29	33
18	18	101	50	68	23
110	15	10	27	70	21
81	24	8	34		

Table 4 (Cont'd). Watershed #11

Sample Point Number	Depth in inches	Sample Point Number	Depth in inches	Sample Point Number	Depth in inches
43	29	87	36	27	32
45	48	90	30	61	55
134	24	41	20	67	24
131	48	125	38	17	36
76	24	121	37	21	35
81	24	117	31	95	22
85	24	29	37		

Table 5. MEAN DEPTH OF PITS FROM FIELD MEASUREMENTS

	$\bar{X}$	$S_{\bar{x}}$	.05 limits	.01 limits
WS#3	26.21	2.85	20.0 - 32.4	17.6 - 34.8
6	40.19	2.52	34.8 - 45.6	32.8 - 47.6
9	29.0	1.89	25.3 - 32.7	24.1 - 33.9
11	32.7	2.14	28.2 - 37.2	26.6 - 38.8
12	29.52	1.70	26.2 - 32.9	24.8 - 34.2
Series 322	34.7	3.75	26.8 - 42.6	23.9 - 45.5
323	33.06	2.41	28.0 - 38.1	26.1 - 40.0
352	25.75	5.27	13.3 - 38.2	7.3 - 44.2
362	30.17	1.32	27.6 - 32.8	26.8 - 33.6
392	32.83	5.21	21.4 - 44.3	16.6 - 49.0

Table 6. Mean pH of soils from soil profile descriptions.

Series	$\overline{x}$	$S_{\overline{x}}$	.05 limits	.01 limits
First Horizon				
322	7.28	.05	7.17 - 7.37	7.13 - 7.43
323	7.22	.02	7.18 - 7.26	7.16 - 7.27
352	6.86	.02	6.82 - 6.90	6.80 - 6.92
362	7.03	.02	6.99 - 7.06	6.98 - 7.08
392	6.88	.02	6.84 - 6.92	6.82 - 6.94
Second Horizon				
322	7.48	.05	7.38 - 7.57	7.34 - 7.61
323	7.36	.02	7.32 - 7.40	7.31 - 7.41
352	7.21	.05	7.16 - 7.32	7.04 - 7.38
362	7.26	.01	7.23 - 7.29	7.22 - 7.30
392	7.27	.03	7.21 - 7.33	7.19 - 7.35
Third Horizon				
322	7.70	.09	7.50 - 7.90	7.43 - 7.97
323	7.40	.03	7.33 - 7.47	7.30 - 7.50
352	7.21	.05	7.10 - 7.32	7.04 - 7.38
362	7.27	.01	7.24 - 7.30	7.23 - 7.31
392	7.28	.03	7.22 - 7.34	7.20 - 7.36

SECTION 5

SAMPLING STUDY OF THE PHYSICAL PROPERTIES OF SEVERAL SOIL TYPES IN NORTHERN ARIZONA

by

James Arthur Ryan

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ABSTRACT

A soil sampling study was made in northern Arizona on four forest watersheds ranging in size from 104 to 1121 acres. Five soil mapping units were represented. The variance of seven soil physical properties were evaluated within and between watersheds among these units in order to test soil sampling schemes for watersheds in the region. For the watersheds studied, it was found that the statistical model used did not always fit the actual field situation. Interestingly, variances did not increase with size of watershed except in a few instances. Simple random sampling was found just as effective for the majority of measurements as stratification by soil mapping units. The study points up some of the inadequacies of standard soil survey methods for describing the hydrologic characteristics of watershed soils.

INTRODUCTION

The Rocky Mountain Forest and Range Experiment Station operates 18 experimental watersheds in the Beaver Creek Area of north central Arizona for the purpose of evaluating the effect of watershed treatments on water yields. The quality, quantity, and timing of water yields are greatly influenced by the physical and hydrologic properties of the soils on these watersheds. Knowledge of soil characteristics is necessary to aid in evaluating treatment effects and extending experimental results to other areas. The various soil types on the watershed have been mapped in accordance with standard soil survey techniques. However, specific information on their physical and hydrologic properties as they vary over broad areas has not been obtained. This study evaluates soil sampling data from four of the experimental watersheds and develops a sampling plan for the general Beaver Creek Area.

Objectives

1. To describe the variation in soil physical properties within and between several soil mapping units and watersheds in the Beaver Creek Area.

2. To develop a sampling scheme to specifically guide sampling of the remaining Beaver Creek experimental watersheds and to serve as a general guide for soil sampling in the area.

Scope

The study was made of soil sampling data from experimental watersheds 3, 6, 9, and 11 which are located on the Mogollon Rim. Data from the 0-3, 3-6, 6-12 and 12-24 inch depths of the Siesta, Sponseller, Brolliar, Gem and Springerville soil series are evaluated and compared. The study is part of a cooperative research project between the U. S. Forest Service and the University of Arizona entitled A Study to Determine the Hydrologic and Physical Properties of Some Beaver Creek Soils (1968).

LITERATURE REVIEW

Most soil sampling studies reported in the literature employed a multiple random sampling technique. Marcuse (1949) described this technique as nested sampling. Using an example of determing the moisture content of cheeses, Marcuse analyzed a three level design. Cheese lots were designated as primary sampling units, individual cheeses as secondary units, and moisture content observations on the individual cheeses as tertiary units. Each observation was described as:

$$Xhij = \quad + E_{h} + n_{hi} + \quad {}_{hij} \tag{1}$$

$h = 1, 2 ---, n_1$ where h refers to the primary unit

$i = 1, 2 ---, n_2$ where i refers to the secondary unit

$j = 1, 2 ---, n_3$ where j refers to the tertiary unit.

The primary objective of this design was to minimize cost of sampling while maintaining a fixed amount of precision or, conversely to maximize precision with a limited cost. To meet these requirements, the optimum number of sampling units at each level was determined by using a cost function and a variance of the mean function. It was necessary to estimate the cost components for the primary, secondary, and tertiary sampling units and calculate variance components for each

of the sampling units. The cost and variance of the mean functions needed for optimum allocation were developed from these components.

Reed and Rigney (1947) used nested sampling to estimate means for soluble phosphorus, exchangeable potassium and calcium, organic matter, and pH on uniform and nonuniform fields in the Piedmont Plateau of North Carolina. The uniform field was a relatively level area of Norfolk fine sandy loam. The nonuniform field was on a rolling topography of Cecil and appling fine sandy loam to clay loam. Primary units were positions evenly spaced over a 3/4 acre area. Secondary units consisted of borings around each position. The tertiary unit was a subsample of the borings. The purpose of the study was to isolate major sources of error in the sampling procedure and to evaluate the effect of reducing some of these errors.

Results showed that in most cases, as would be expected, variation between the primary sampling units was greater for the nonuniform field. Although mean values for organic matter differed greatly between the two fields, primary unit variations were similar. It was concluded that each soil property might have a unique variation pattern; stratification had no effect; and that often more precision is used in the laboratory than necessary.

Mason, Lutz, and Peterson (1957) expanded the methods of Marcuse over a wide range of soil conditions in seven states. Data was obtained from about 900 sites and 10,000 core samples; sites and

core samples being the primary and secondary sampling units respectively. Measurements were made of hydraulic conductivity, percent large pores, and bulk density. Samples were stratified according to soil type-management-horizon units. Variance components for the primary and secondary units were determined in the same manner as the above studies. Cost and variance of the mean functions were computed in order to determine optimum allocation. It was found that variation between primary sampling units was two to three times greater than between secondary units.

Hammond, Pritchett, and Chew (1958) performed a similar study in Florida on seven fields including six soil types. Soil moisture, pH and extractable K, Ca, Mg, and P were estimated with the three level design of Marcuse. The study also included a comparison of multistage sampling to simple random sampling expressed by the ratio

$$E = \frac{\text{Variance of the mean, simple random sampling}}{\text{Variance of the mean, three stage sampling}} \qquad (2)$$

where E is the relative efficiency. Percentage increase in efficiency was as high as 80 percent.

Results showed an interesting pattern in variation. In many cases, variation was almost as great within small areas as within larger areas. These phenomena were described by the term "macro-uniformity." It occurred with soil moisture on all seven fields. Within each field at least three other properties exhibited this characteristic. The variance

component breakdown showed the tertiary units made an insignificant contribution to the total variation.

Sayegh, Alban, and Peterson (1958) sampled a 12 square mile transect in the Baker Valley Area, Oregon for hydraulic conductivity and exchangeable sodium. The transect was divided into seventy-five, 6.4 acre locations. Each soil mapping unit contained a number of locations in proportion to its area. Some of the locations were further subsampled in order to determine variation within locations. The data were analyzed by the methods described by Marcuse (1949). An F ratio calculated from the variation between soil mapping units, and the variation between locations was barely significant for conductivity and was not significant for exchangeable sodium.

Aljibury and Evans (1961) tested the reliability of stratifying strictly by soil mapping units when estimating means. Measurements were made over two Oregon counties on 0.1, 0.5, 1, 5, 10, and 15-bar suctions and bulk density. Two soil series were dominate, Deschuter and Redmond. Both were thought to be relatively uniform. All township sections containing either one or both of these soils were numbered and divided into 36 tracts. The tracts to be sampled were selected at random and measurements taken on two sites within tracts. The means measurements were analyzed in the same manner as in the previous studies.

Results showed differences in means between soil groups, counties and depths for bulk density and the 0.1 and 15-bar percentages. No differences were shown between soil groups for the moisture percentages between 0.1 and 15-bars. Variation within tracts was found to be as great as variation between tracts. Because of the nature of the variation, it was concluded that using a general estimate for a soil group was not good when considering a particular small area.

Ike and Clutter (1968) also evaluated stratification criteria with measurements of chemical and physical properties on 123 forested plots in the Blue Ridge Mountains of northeast Georgia. Primary and secondary sampling units consisted of 0.2 acre plots and 4 pits within each plot. Stratification significantly reduced variation when based on soil series but not soil type.

METHODS

Study Areas

The Beaver Creek Area covers 302,205 acres and ranges in elevation from 3,100 feet to 8,500 feet. Over three-quarters of the area is underlain by volcanic rocks such as tuff, agglomerate, cinders, and basalt. These are the parent materials for the soils sampled in this study. The topography of the area is characterized by gentle slopes which have permitted moderately deep weathering and soil profile development. The higher elevations support a ponderosa pine type on Brolliar, Siesta, and Sponseller soils. Below the pine zone the pinon-juniper woodland type is predominate on soils in the Springerville and Gem series. The climate of the area is semi-arid and continental with cold winters and warm summers at the higher elevations, and mild weather year round in the lower areas. A more detailed description of the area is given by Williams and Anderson (1967).

The watersheds selected for this study represent different vegetation and precipitation zones. Watershed 3, covering an area of 362 acres, is located at an elevation of about 5500 feet within pinon-juniper vegetation type. Utah juniper is the principal overstory species. There is little or no understory. Annual precipitation averaged over a nine

year period is about 18 inches. Only soils of the Springerville series are represented on the watershed. They are characteristically vertisols developed from the weathering of basalt and cinders. The clay fraction is almost entirely montmorillonite which causes pronounced shrinking and swelling.

Watershed 6 is about 1000 feet above watershed 3 and is also in the pinon-juniper vegetation zone. However, the original overstory was alligator juniper rather than Utah juniper. In 1965 the overstory was cleared and a moderate cover of grass was established. The watershed's 104 acres receives an average annual precipitation of 20 inches which is evenly distributed between the summer and winter seasons. Soils on the watershed are principally in the Springerville and Gem series. The Gem series is distinguished by moderately deep to deep soils ranging in color from dark brown at the surface to reddish yellow and brown at the lower depths. Surface layers have a granular structure when dry, and sub-strata are massive. Rocks are prominent on the surface.

Watershed 11 borders between the pinon-juniper and pine type at 6800 feet elevation. All 199 acres of the watershed were cleared of the original stand of ponderosa pine, Gambel oak, and alligator juniper in 1958, and a dense cover of grass was established. Precipitation averages 22 inches per year. Gem and Brolliar are the two predominant soil series. The Brolliar series is characterized by deep to moderately

deep profiles weathered from porous basalts. The dark brown surface is platy in structure. The subsoil is reddish brown with a blocky structure. Rocks cover 20-60 percent of the surface.

Watershed 9, covering 1121 acres, is in the pine zone with ponderosa pine, Gambel oak, and some alligator juniper composing most of the overstory. The understory is mainly grasses and forbs. The watershed is at an elevation of 7500 feet where annual precipitation is about 27 inches. In addition to the above described soil series Brolliar, Sponseller and Siesta are the major soil series on this watershed. The Siesta soil series is moderately deep and usually reddish brown throughout the profile. Structure ranges from platy and granular at the surface to massive in the subsoil. Sponseller soils were formed from volcanic cinder material. Color ranges from a dark reddish brown at the surface to yellowish red near the parent cinder material. These soils have a tendency to be slightly acid to neutral. Like the other soils on the watershed, structure ranges from granular and platy to massive.

Field Sampling

The sampling populations were restricted to watersheds 3, 6, 9, and 11. A population is defined as a particular soil depth over all the soil series represented on a watershed. The soil depths sampled were 0-3 inches, 3-6 inches, 6-12 inches, and continued in one foot increments to the parent material. Nested sampling as described by

Marcuse (1949) was used. However, a two level design was used with soil sampling pits being the primary sampling units and subsamples within pits being the secondary units. Locations for the pits were selected at random over a watershed using previously established vegetation inventory points. The inventory points had been established by the technique of multiple random starts. The sample point numbers were selected from a table of random numbers. Sample pits were located in most cases one chain down-slope from the point. Locations and numbers of pits on the four watersheds are given in A Study to Determine the Hydrologic and Physical Properties of Some Beaver Creek Soils (1968).

The pits were dug by a backhoe furnished with an operator by the Coconino National Forest. Pits were dug to seven feet or parent material which ever came first. Three subsamples were then taken from the sides of the pit at each depth down to the parent material. A subsample consisted of a quart paper container filled with soil and labeled with pit, depth, and subsample number. Determinations for texture, soil moisture at .33, .66, 3, 5, 10 and 15 bars, bulk density and organic matter were made on these samples. Laboratory methods used are described in A Study to Determine the Hydrologic and Physical Properties of Some Beaver Creek Soils (1968).

ANALYSIS

The laboratory data were analyzed by several methods. In order to determine whether variation differed with size of watershed and the number of soil series present, the homogeneity of the estimated mean squares for primary units was tested using Bartlett's statistic (Li, 1964). Homogeneity of means between watersheds, soil series and soil soil series within watersheds were tested using Duncan's New Multiple Range and Student's T tests. A precision level of five percent was used for all tests.

The variance of the mean was calculated in two ways. First, the estimated mean square for primary sampling units in the described analysis was calculated for each depth over an entire watershed and divided by the total number of subsamples. The second method was done in the same manner excepting that a variance of the mean was calculated for each depth within each soil series within a watershed. Then a post-stratified variance of the mean for the 0-3 inch depth was determined by

$$V(\bar{x}) = 1/n\Sigma W_h^2 + 1/nEW_h(1 - W_h)\frac{S_h^2}{} \qquad (3)$$

where W_h is the stratum weight for soil series h, S_h^2 is the expected mean square for soils series h, n_h is the number of subsamples within

soil series h, and n is the total number of subsamples (Kish, 1965). Stratum weights were based on the proportion of area covered by a particular soil series. The variance of the mean determined from the random sample was divided by the post-stratified variance of the mean giving the relative efficiency of stratifying.

The analysis of the optimum allocation sampling problem of this study is virtually the same as described by Marcuse (1949). However, because of unequal subclass numbers, a two level rather than a three level design was used. In this design an individual observation X is expressed as

$$X_{hi} = \mu + E_h + N_{hi} \tag{4}$$

where h refers to pits $(h = 1, 2, \text{---}\ n_1)$

and

where i refers to subsamples $(i = 1, 2, \text{---}\ n_2)$.

The constant μ is the population mean and E and N are random variables having means and covariances of zero and variances equal to σ^2, and σ_2^2. These two variance components are needed to develop the variance of the mean function.

$$\sigma_{\bar{x}}^2 = \frac{\sigma_1^2}{n_1} + \frac{\sigma_2^2}{n_1 n_2} \quad . \tag{5}$$

However, these components are unknown and must be estimated in order

to use the function. This is done by analysis of variance of the sampling data.

The basic analysis of variance for nested sampling is given in Table 1 for equal subclass numbers.

Table 1. Analysis of Variance in Two-Fold Nested Sampling

Source of Variation	Degrees of Freedom*	Expected Mean Squares
Primary sampling units	$n_1 - 1$	$\sigma_2^2 + n_2\sigma_1^2$
Secondary units	$n_1(n_2 - 1)$	σ_2^2

*n_1 = number of primary units

The value of n_2 in the expression for the expected mean square of primary sampling units,

$$EMS = \sigma_2^2 + n_2\sigma_1^2 \tag{6}$$

is the number of subsamples within each pit. If all pits had three subsamples at each depth n_2 would equal three. However, because of missing data this is not always the case (Fryer, 1966). For missing data, the value of n_2 is calculated from the expression

$$n_2 = \sum_h (n_h^2 f_h) . \tag{7}$$

The number of subsamples in pit h is referred to as n_h. The value of f_h for pit h is determined from

$$f_h = (1/n_h - 1/n)/(a - 1) \tag{8}$$

where n is the total number of subsamples for all pits and (a - 1) is the degrees of freedom for the primary sampling units. In order to estimate the expected mean squares the sum of squares for primary sampling units, SS_1, and the secondary units, SS_2, are calculated by:

$$SS_1 = \Sigma_h (x_{hi})^2/n_h - (\Sigma x_{hi})^2/n \tag{9}$$

$$SS_2 = \Sigma (x_{hi})^2 - SS_1 \; . \tag{10}$$

The sums of squares are then divided by their respective degrees of freedom giving the estimated mean squares

$$MS_1 = S_2^2 + n_2 S_1^2 \tag{11}$$

and

$$MS_2 = S_2^2 \tag{12}$$

The estimated variance components S_1^2 and S_2^2 are then used in the optimum allocation problem.

Expression for the optimum number of primary and secondary units are developed from the cost function

$$C(n_1, n_2) = C_1 n_1 + C_2 n_1 n_2 \tag{13}$$

and the variance of the mean function

$$V(n_1, n_2) = \frac{S_1^2}{n_1} + \frac{S_2^2}{n_1 n_2} \tag{14}$$

Values for S_1 and S_2 were calculated as previously described. The constants C_1 and C_2 are estimated on the basis of man hours spent in the field and laboratory. They represent the cost in locating and sampling a pit and the cost of taking and analyzing an individual sample. The relative number of pits n_1 to the number of subsamples within each pit n_2 are determined one of two ways. If a fixed amount of precision is given V then the expressions

$$n_{c1} = \frac{S_1}{V} \sum_{i=1}^{2} (S_i \sqrt{C_i}) / \sqrt{C_1} \tag{15}$$

and

$$n_{c2} = \frac{S_2}{S_1} \sqrt{C_1/C_2} \tag{16}$$

are used. However, if the least possible variation is desired for a limited total cost C then the expressions

$$n_{v1} = \frac{S_1}{\sum_{i=1}^{2} (S_i \sqrt{C_i})} \, C/\sqrt{C_1} \qquad (17)$$

and

$$n_{v2} = \frac{S_2}{S_1} \sqrt{C_1/C_2} \qquad (18)$$

are used. A detailed development of these expressions is found in Marcuse (1949).

RESULTS AND DISCUSSION

Results of the study are separated into four categories: (1) comparison of soil property means by the Student's T test and Duncan's New Multiple Range test, (2) effects of stratification based on relative efficiency determined by ratios of the stratified and simple random variances of the mean, (3) relationships of variation to watershed size based on the results of Bartlett's test, and (4) a sampling scheme for the Beaver Creek Area using estimated costs and variances for both a fixed cost and precision situations.

Comparison of Soil Property Means

Comparisons Between Watersheds

Results of the Duncan's New Multiple Range tests are given in Tables 1 and 2 of the appendix. Student T tests and all non-significant results are not given in the tables. Several consistent patterns are pointed out by the tests. In comparing soil textures between watersheds, sand content on watershed 9 was significantly higher than on watershed 6 throughout the first 12 inches of soil depth. Below three inches, sand content was also greater than on watershed 3. Sand content was significantly greater on watershed 9 than on the other watersheds at the 6-12 inch depth. Percentage of silt was uniform between all watersheds with

the exception of watershed 3 where it was significantly lower in the upper six inches. Clay content for the soils on watershed 3 was consistently higher than that of watersheds 11 and 9, and greater than on all other watersheds at the 6-12 inch depth.

Soil water retention at both .33 and .66 bars suction was consistently higher for watershed 3 than for the other watersheds at all depths. Differences were significant at 0-3 and 3-6 inches. No significant differences existed among the other watersheds at any of the soil depths. Bulk density values did not differ on watersheds 3, 6 and 9, but were significantly lower on watershed 11 throughout all depths. The only significant difference between organic matter content was the higher amount in the soils of watershed 9, especially below the 0-3 inch depth.

Comparisons Between Soil Series

There were fewer differences between soil series than between watersheds. The Gem series consistently had a lower sand content than the Siesta series at all depths. Silt content was essentially uniform over all five soil series. Clay content of the Siesta and Sponseller series was significantly lower than that of Gem and Springerville. Soil water retention at both suctions was similar over all depths in the five series. Bulk density for the Siesta and Sponseller series was consistently lower than for the Gem at all depths. All comparisons of organic

content showed the Springerville and Gem series to have lower values than Siesta and Sponseller.

Comparison Within Watersheds

Differences between soil properties were least between soil series within watersheds. The only significant differences occurred on watershed 6 between the Gem and Springerville series where silt and clay content and soil water retention were significantly different in the two depths below three inches.

Summary of Comparisons

Differences in soil physical properties were more pronounced between watersheds than between soil series. The means of a number of soil properties were uniquely different between individual watersheds whereas they often appeared to be grouped between two or more soil series. For example, the soils of watershed 9 had a higher percentage of sand, and those of watershed 3 tended to be higher in clay content than those of other watersheds.

The grouping of similar means appeared to have some relationship to location. Soil properties of Siesta and Sponseller were often significantly different that those of Gem and Springerville. Clay content was always significantly higher for Springerville and Gem than that for Siesta and Sponseller. Siesta and Sponseller are only present on watershed 9 while Springerville and Gem are located on the pinon-juniper and marginal pine watersheds.

With the exception of watershed 6, there were no significant differences between soil series within watersheds. It appears that in the Beaver Creek region, any differences in soil physical characteristics that might be associated with the broad, often arbitrary, features used in soil classification are outweighed by those due to the unique interrelationships of vegetation, parent material, and climate on local areas.

The apparently contradictory results found on watershed 6 may lend support to this idea. The Gem and Springerville series on the watershed differed significantly in several soil properties. However, they did not differ when considered over all watersheds. This points up that local phenomena control soil properties and that more fundamental methods based on local homogeneity are needed for stratification. The question of what factor controls soil homogeneity needs to be answered. Perhaps an analytic method of stratification based on sampling data might be used.

Relative Efficiency of Stratification by Soil Mapping Units

The precision gained when stratifying by soil series within a watershed is given in Tables 3 through 6 of the appendix. In nearly all of the 18 cases tested the gain in precision was slight or even negative. Only six of the tests showed gains above 10 percent. Among these, four had gains greater than 20 percent, three greater than 30 percent, and only one showed a gain in precision of over 40 percent. Considering these

results and the added difficulty of taking a stratified sample over a simple random sample, stratifying by soil mapping units would have no advantage in this study.

The results point up the weakness of using characteristics other than those of the quantity being measured as a basis for stratification. A particular quantity may have a low variation in a strata that is given more weight because of some other characteristic. For example, bulk density sampling efficiency would have been decreased 60 percent on watershed 9 if stratification had been on the basis of soil mapping units (Appendix, Table 6). This is due to the necessity of taking a disproportionately large number of samples on the area of Brolliar soils which covered about 70 percent of the area but which also showed the least variation. The results may also reflect the "macro-uniformity" described by Hammond, Pritchett, and Chew (1958) where variation within small areas was as great or greater than over large areas.

Homogeneity of Variances

Bartlett's test for the homogeneity of variances for the soil properties sampled showed little relationship between size of area and degree of variation. Indeed, where there were significant differences in variances between watersheds, the general trend was sometimes toward lower variances for the larger watersheds. For example, variations for bulk density on all four watersheds were not significantly different as

shown by the chi square value given in Table 2. This means that watershed 6 with an area of about 100 acres has as much variation in soil bulk density as watershed 9 which is over 1000 acres. The variations for silt and clay at 0-3 inches are significantly different. However, there is no increase in variability with increase in size as shown in Figure 1. Another interesting result was that watershed 3 with only one principal soil series often had greater variation than watershed 9 which has three principal series.

Sampling Scheme

When solving the optimum allocation sampling problem, both cost and variation must be considered. The cost components given in Table 3 were determined from field and laboratory experience. They were estimated for conditions of maximum efficiency where no allowance is made for lost time. Field sampling was done with a crew of three men, one operating a backhoe and two sampling. More men would not have decreased sampling time appreciably and fewer would have reduced efficiency. Two laboratory technicians were required and it was necessary to streamline laboratory methods in order to handle the large quantity of samples taken in the study. In figuring total cost, an initial cost of transporting men and equipment to the watershed site should also be considered. But since this will vary for every situation, it was not included in this study.

Table 2. Chi-Square Values for Bartlett's Test of Homogeneity of Variances between Watersheds for Soil Physical Properties

Depth in Inches	Sand	Silt	Clay	Suction .33 Bars	Suction .66 Bars	Bulk Density	Organic Material
0-3	19.689*	2.5162	23.1004*	10.5947*	2.7442	2.26	74.58975*
3-6	14.0235*	13.0235*	17.916306	6.2495	27.3475	2.23	4.04206
6-12	35.0407*	4.6584*	11.37815*	11.5789*	5.2548	2.54	1.18656
12-24	15.767*	9.7650	8.71695*	41.4159*	26.6603*		15.27989*
24-36	3.1165	9.4959*	1.2667	26.1455*	46.6687*		8.09556*

*Significant at five percent.

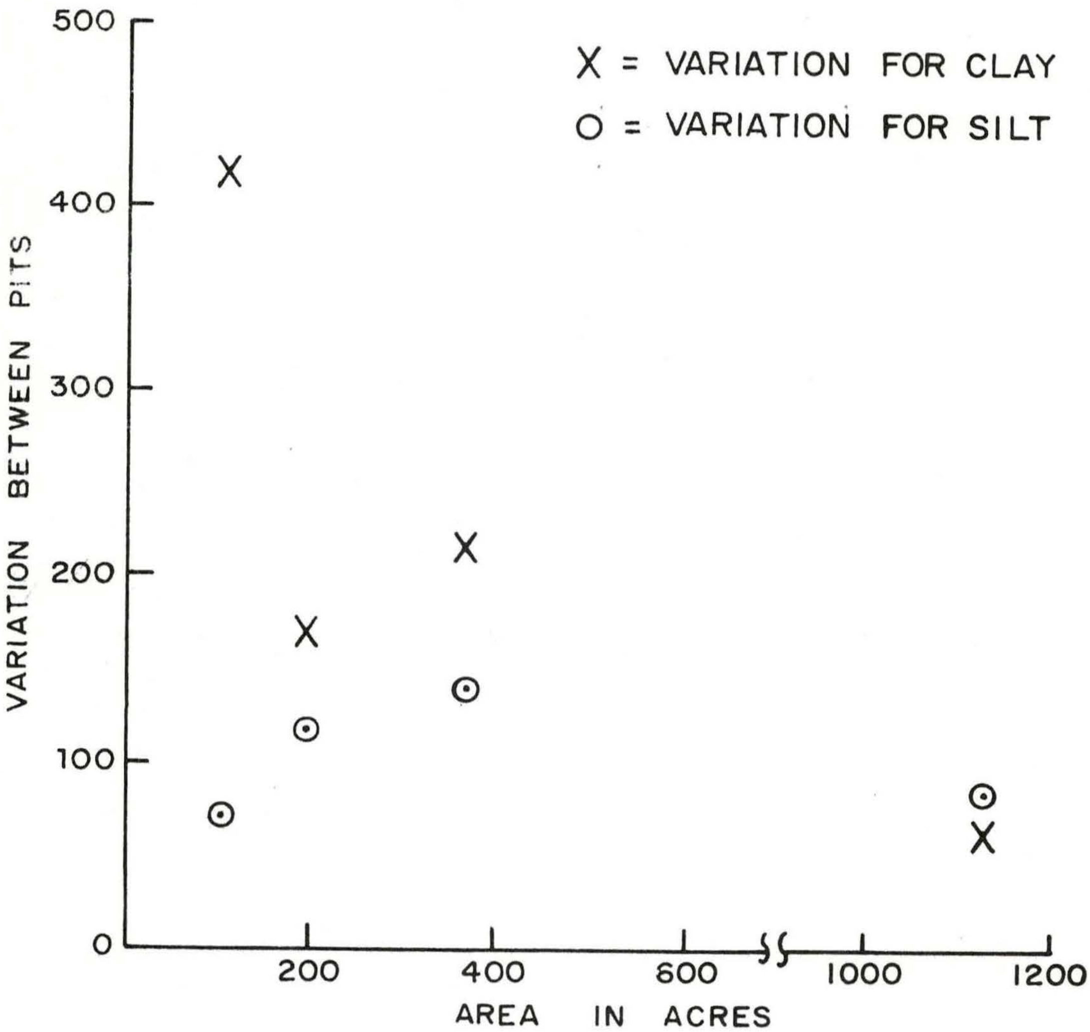

Figure 1. Comparison of Variance to Area for Clay and Silt at the 0-3 Inch Depth on All Watersheds

Table 3. Estimated Laboratory and Field Costs in Man Hours

Field Cost		Laboratory Cost	
locating pits	.5	preparation	.20
travel	.5	bulk density	.10
digging	.5	texture	
		weighing	.07
sampling	1.5	dispersion	.01
		filling cylinders	.13
		readings	.02
		cleaning equipment	.03
		organic material	.22
		soil suction	.11
		conductivity	.51
Total	3.0		1.40

The travel time listed in Table 3 only includes time spent moving from one pit to another after men and equipment were on the watershed. Soil preparation, included in the laboratory costs, refers to breaking and grinding air-dried soils into workable form. This expense must be added to the cost of all determinations with the exception of bulk density.

The variance components were estimated for the soil properties of watersheds and soil series within watersheds (Appendix, Tables 3 through 13). It was not uncommon for the variance component for pits to be smaller than the subsample variance component. This again reflects the "macro-uniformity" phenomenon. More interestingly, variance components for several soil properties at various depths could not be estimated using the expected mean squares of Table 2, because the estimated mean square for primary units was smaller than the estimated mean square for secondary units. This indicates that the statistical model used in the study did not always fit the actual field situation. Thus, the basic assumptions made in all previous soil sampling studies may not hold for all soil populations. It is apparent that further study of the distribution of physical soil properties for various populations is needed.

The estimated cost and variance components were used to calculate the optimum number of soil pits and subsamples while maximizing the precision with a limited cost or minimizing cost with a fixed

precision. These values are also given in Appendix, Tables 3 through 13. Cost was limited to 50 man hours for sampling and analyzing one soil property. Precision was fixed with 10 percent of the mean 95 percent of the time.

An unrealistically high sample size was required to maintain the chosen level of precision for sand and organic matter on all watersheds. This is explained by the fact that both properties have small means, and measurement error alone is quite high on a percentage basis. Where extremely large sample sizes are needed to maintain a high precision, the optimum values with limited cost must be considered. For example, in order to measure sand content at the 3-6 inch depth on watershed 3, 118 pits and 3 subsamples per pit are needed to be within 10 percent of the mean. With a limited cost of 50 man hours, only 12 pits and the same number of subsamples can be taken, giving a precision of about 30 percent of the mean. Conversely, bulk density required only one or two pits and several subsamples for the fixed precision. Variances were quite low, and variance components for subsamples often were higher than the pit variance components.

Example of the Optimum Allocation Problem

The following is an example of optimum allocation using the determined silt percentate for the 0-3 inch layer of soil on watershed 3. The analysis of variance for silt content on watershed 3 at the 0-3 inch

depth is given in Table 4. Since four of the 14 pits sampled had six rather than the usual subsamples, equation (7) gives a value of 3.76 for n_2 rather than 3.

Table 4. Analysis of Variance of Silt Content Percentages on Watershed 3 at 0-3 Inch Depth

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Squares	Expected Mean Squares
Pits	13	$SS_1 = 1857.05$	142.85	$S_2^2 + 3.76\ S_1^2$
Subsamples within pits	39	$SS_2 = 787.80$	20.20	S_2^2
Total	52	2644.85		

With the information in Table 4 estimated variance components S_1^2 and S_2^2 determined with equations (11) and (12) are 32.62 for pits and 20.20 for subsamples, respectively. Costs are $C_1 = 3$ man hours to sample each pit and $C_2 = 0.46$ man hours to analyze each subsample (Table 3). A precision of 10 percent within the mean and a limited cost of C - 50 man hours is chosen. Since silt content has a mean of 40.99 percent (Appendix, Table 3), the fixed variance V is calculated to be 4.02 using the expression

where d is the allowable deviation from the mean and t is taken at the five percent level.

The above values are all that is needed to solve the optimum allocation problem. When used in equations (15) and (16), the solutions for the fixed precision situation is $n_{c1} = 10$ and $n_{c2} = 2$. The cost and variance components introduced into equations (17) and (18) gives $n_{v1} = 13$ and $n_{v2} = 2$.

The optimum solutions for both the fixed precision and the limited cost situations are illustrated in Figures 2 and 3. The fixed precision chosen for the example gives a coefficient of variation of about five percent. The curves in Figure 2 show that this precision can be maintained with sample sizes of 15 pits and one subsample, nine pits and four subsamples, and the previously calculated solution of 10 pits and two subsamples. The curves of Figure 3 show a cost of 52 man hours for 15 pits and one subsample, 44 man hours for nine pits and four subsamples, and 40 man hours for the calculated example. With the limited cost of 50 man hours the choice is: (1) 15 pits and one subsample, (2) 13 pits and two subsamples, or (3) 11 pits and four subsamples. From Figure 2, 13 pits with two subsamples is the best choice.

The curves in Figure 2 also show that increasing the number of subsamples beyond two does not add significantly to precision.

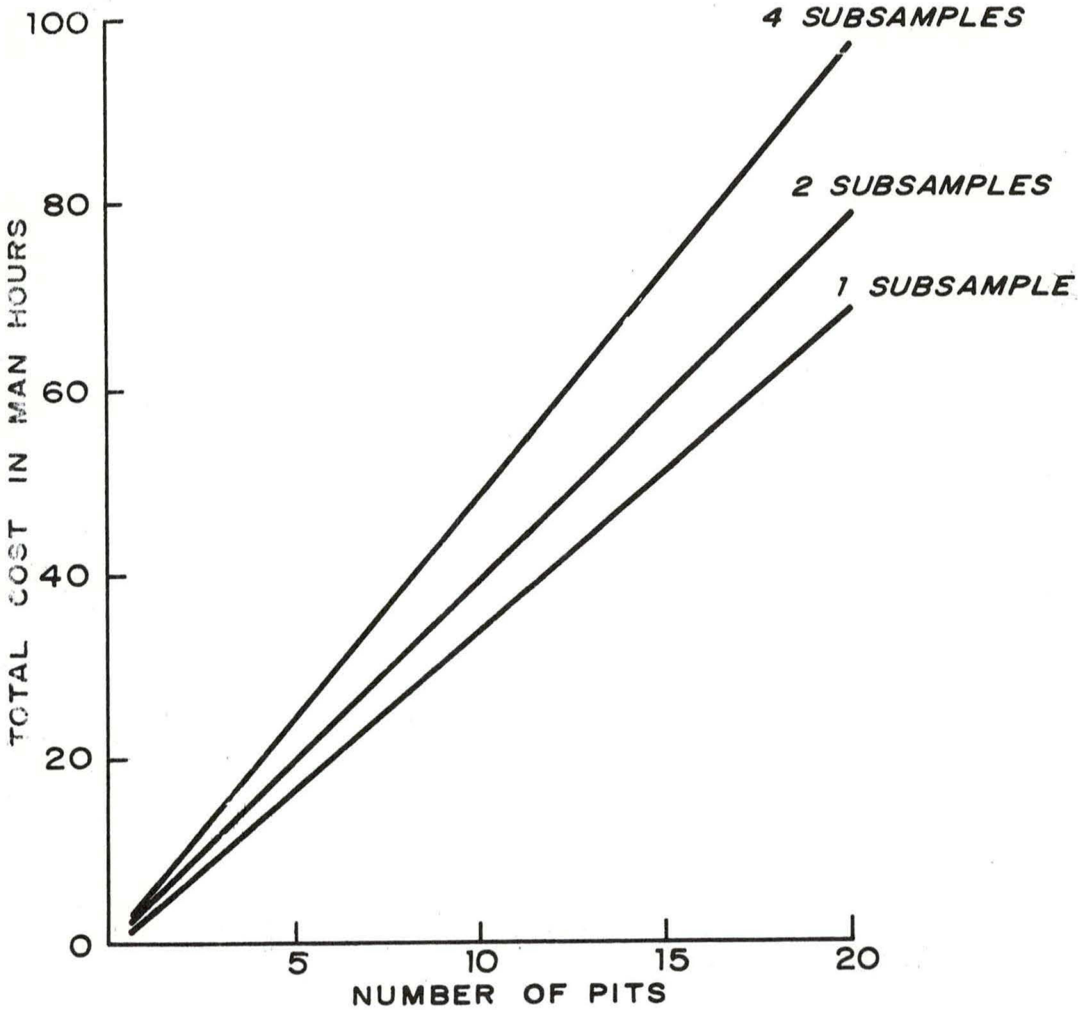

Figure 3. Effect of Number of Pits and Subsamples on Total Cost of Sampling Silt Content at 0-3 Inch Depth on Watershed 3

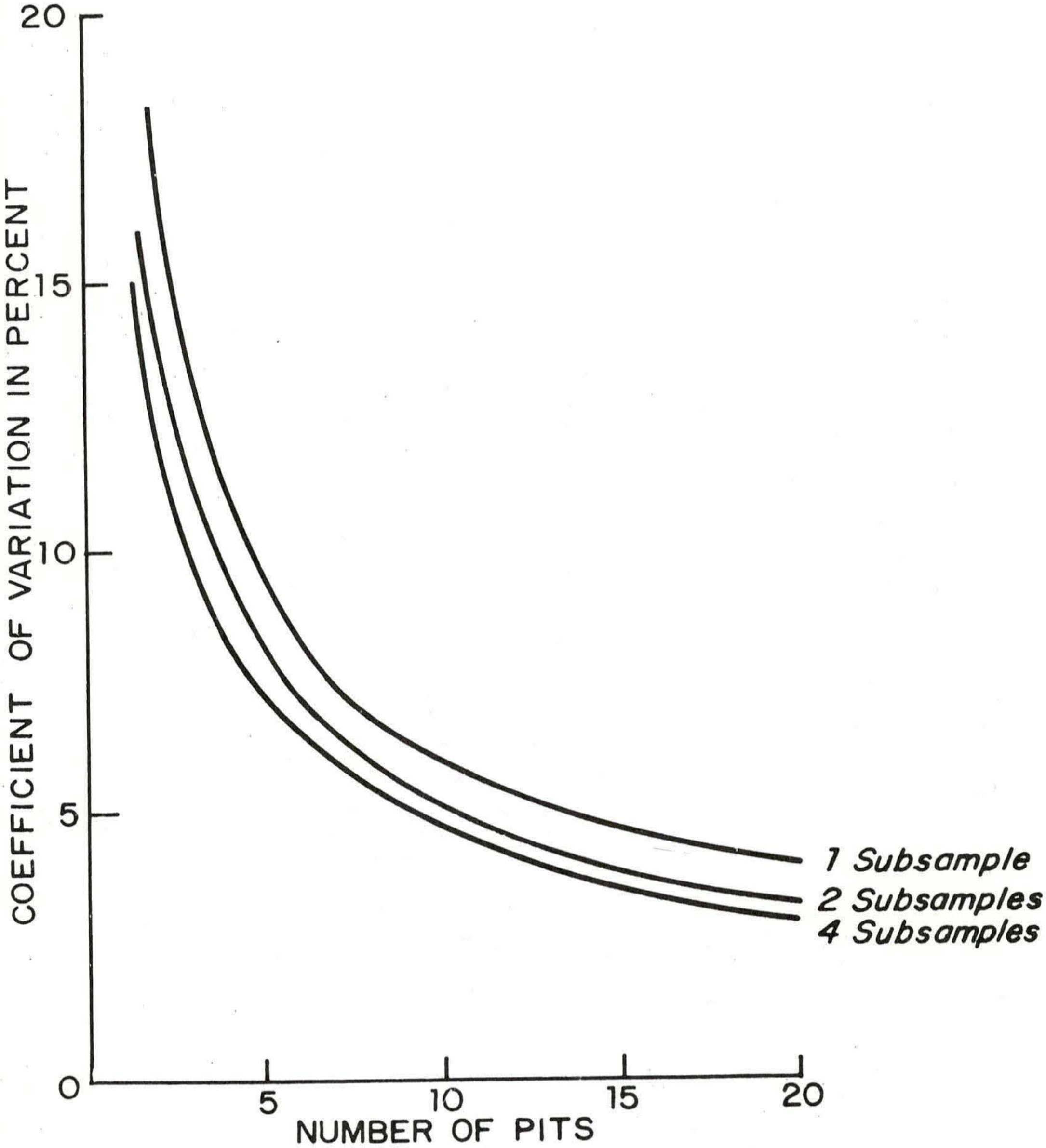

Figure 2. Effect of Number of Pits and Subsamples on Precision for Silt Content at 0-3 Inch Depth on Watershed 3

CONCLUSIONS

The following conclusions were drawn from the results of the study:

1. In the Beaver Creek region, any difference in soil physical characteristics that might be associated with broad, often arbitrary features used in soil classification are outweighed by those due to the unique inter-relationships of vegetation, parent material, and climate in local area.

2. Stratifying by soil mapping units on a watershed would have had no advantage over a simple random sample. More fundamental units for stratification based on local homogeneity are needed.

3. The magnitude of variation for soil physical characteristics had little relationship with size of area or number of soil series on a watershed.

4. The basic statistical model used for most soil sampling studies did not always fit the actual field conditions in this study, indicating previous assumptions, in some cases, may be invalid.

APPENDIX

Table 1. Duncan's New Multiple Range Test for Soil Physical Properties between Watersheds

Sand, 0-3 Inch Depth

Watershed 6	Watershed 11	Watershed 3	Watershed 9
10.19	12.77	14.32	20.36

Sand, 3-6 Inch Depth

Watershed 6	Watershed 3	Watershed 11	Watershed 9
6.81	7.45	10.08	18.43

Sand, 6-12 Inch Depth

Watershed 6	Watershed 11	Watershed 3	Watershed 9
7.19	7.61	7.62	16.62

Table 1--Continued

Silt, 0-3 Inch Depth

Watershed 3	Watershed 6	Watershed 9	Watershed 11
40.99	50.34	51.33	51.78

Silt, 3-6 Inch Depth

Watershed 3	Watershed 6	Watershed 11	Watershed 9
37.48	46.39	46.93	48.07

Clay, 0-3 Inch Depth

Watershed 9	Watershed 11	Watershed 6	Watershed 3
28.33	35.06	39.59	44.70

Clay, 3-6 Inch Depth

Watershed 9	Watershed 11	Watershed 6	Watershed 3
33.54	43.34	46.68	54.29

Table 1--Continued

Clay, 6-12 Inch Depth

Watershed 9	Watershed 6	Watershed 11	Watershed 3
40.68	50.88	52.20	63.33

Soil Water Retention at .33 Bars, 0-3 Inch Depth

Watershed 9	Watershed 6	Watershed 11	Watershed 3
28.32	28.33	28.76	34.21

Soil Water Retention at .33 Bars, 3-6 Inch Depth

Watershed 9	Watershed 11	Watershed 6	Watershed 3
26.89	29.37	29.95	35.15

Soil Water Retention at .33 Bars, 6-12 Inch Depth

Watershed 9	Watershed 6	Watershed 11	Watershed 3
30.20	32.14	32.90	36.34

Table 1--Continued

Soil Water Retention at .66 Bars, 0-3 Inch Depth

Watershed 6	Watershed 11	Watershed 9	Watershed 3
24.16	25.05	25.37	30.63

Soil Water Retention at .66 Bars, 3-6 Inch Depth

Watershed 6	Watershed 11	Watershed 9	Watershed 3
24.16	25.05	25.37	30.63

Soil Water Retention at .66 Bars, 3-6 Inch Depth

Watershed 9	Watershed 6	Watershed 11	Watershed 3
24.42	25.97	26.09	31.44

Bulk Density, 0-3 Inch Depth

Watershed 11	Watershed 3	Watershed 6	Watershed 9
1.62	1.71	1.78	1.80

Table 1--Continued

Bulk Density, 3-6 Inch Depth

Watershed 11	Watershed 9	Watershed 6	Watershed 3
1.54	1.66	1.71	1.72

Bulk Density, 6-12 Inch Depth

Watershed 11	Watershed 3	Watershed 6	Watershed 9
1.61	1.75	1.78	1.79

Organic Content, 0-3 Inch Depth

Watershed 3	Watershed 6	Watershed 11	Watershed 9
.9983	1.0763	1.5939	2.6132

Organic Content, 3-6 Inch Depth

Watershed 6	Watershed 11	Watershed 3	Watershed 9
.7959	.8875	.9693	1.6347

Table 1--Continued

Organic Content, 6-12 Inch Depth

Watershed 6	Watershed 11	Watershed 3	Watershed 9
.5510	.6774	.7380	1.0477

Table 2. Duncan's New Multiple Range Test for Soil Physical Properties between Soil Series

Sand, 0-3 Inch Depth

Gem	Springerville	Brolliar	Sponseller	Siesta
10.13	13.72	17.5	20.20	22.75

Sand, 3-6 Inch Depth

Springerville	Gem	Brolliar	Sponseller	Siesta
7.60	7.64	15.59	16.64	19.53

Sand, 6-12 Inch Depth

Gem	Springerville	Brolliar	Sponseller	Siesta
6.69	7.85	13.38	14.90	19.93

Table 2--Continued

Silt, 3-6 Inch Depth

Springerville	Gem	Brolliar	Siesta	Sponseller
39.75	44.28	47.20	49.83	50.64

Clay, 0-3 Inch Depth

Siesta	Sponseller	Brolliar	Gem	Springerville
26.49	27.82	30.63	40.49	42.49

Clay, 3-6 Inch Depth

Siesta	Sponseller	Brolliar	Gem	Springerville
30.54	33.09	37.09	48.08	51.93

Clay, 6-12 Inch Depth

Siesta	Sponseller	Brolliar	Gem	Springerville
35.88	40.0791	45.75	54.99	55.18

Table 2--Continued

Soil Water Retention at .33 Bars, 3-6 Inch Depth

Siesta	Brolliar	Sponseller	Gem	Springerville
24.90	27.45	27.77	30.84	33.68

Bulk Density, 0-3 Inch Depth

Siesta	Sponseller	Brolliar	Gem	Springerville
1.35	1.43	1.48	1.60	1.61

Bulk Density, 3-6 Inch Depth

Sponseller	Siesta	Brolliar	Springerville	Gem
1.48	1.49	1.60	1.71	1.72

Bulk Density, 6-12 Inch Depth

Siesta	Sponseller	Brolliar	Springervile	Gem
1.56	1.58	1.70	1.72	1.82

Table 2--Continued

Organic Content, 0-3 Inch Depth

Springerville	Gem	Brolliar	Siesta	Sponseller
1.03	1.35	2.12	2.22	2.82

Organic Content, 3-6 Inch Depth

Gem	Springerville	Brolliar	Sponseller	Siesta
.83	.90	1.34	1.77	1.86

Organic Content, 6-12 Inch Depth

Gem	Springervile	Brolliar	Siesta	Springerville
.57	.72	.91	1.05	1.26

Legend for Tables 3 through 13

$\overline{X}$	mean
EMS	estimated mean square for pits
DF	degrees of freedom for EMS
S_1^2	variance component for pits
S_2^2	variance component for subsamples
n_{c1}	optimum number of pits with fixed precision
n_{v1}	optimum number of pits with limited cost
n_2	optimum number of subsamples
RE	relative efficiency of a stratified sample

Table 3. Means, Estimated Mean Squares, Variance Components, and Solutions to the Optimum Allocation Problem for Soil Physical Properties on Watershed 3

Depth in Inches		Sand	Silt	Clay	Suction .33 Bars	Suction .66 Bars	Bulk Density	Organic Material
0-3	$\overline{X}$	14.32	40.99	44.70	34.21	30.63	1.71	.9983
	EMS	147.15	142.85	216.38	65.19	66.99	.03884	.3423
	DF	13	13	13	13	13	13	13
	S_1^2	34.16	32.62	52.75	11.38	13.64	.00324	.1233
	S_2^2	18.69	20.20	18.03	15.69	15.69	.002645	.02675
	n_{cl}	83	10	12	8	8	1	58
	n_{vl}	13	13	15	12	12	11	14
	n_2	2	2	1	3	3	16	1
3-6	$\overline{X}$	7.45	37.48	54.29	35.15	31.44	1.72	.8875
	EMS	59.31	92.61	89.55	33.93	199.88	.0239	.2738
	DF	13	13	13	13	13	13	13
	S_1^2	12.22	19.31	12.88	6.74	56.60	.0049	.0891

Table 3--Continued

Depth in Inches		Sand	Silt	Clay	Suction .33 Bars	Suction .66 Bars	Bulk Density	Organic Material
	S_2^2	12.62	18.86	40.34	8.56	2.10	.00555	.01271
	n_{cl}	118	7	3	3	22	1	53
	n_{vl}	12	12	10	12	16	14	14
	n_2	3	3	5	4	1	6	1
6-12	$\overline{X}$	7.62	34.65	63.33	36.34	32.68	1.75	73.80
	EMS	67.17	60.70	66.33	58.50	40.75	.02642	.1915
	DF	13	13	13	13	13	13	13
	S_1^2	15.10	13.73	15.20	13.99	7.37	.00164	.0610
	S_2^2	9.50	8.27	6.25	5.87	13.60	.02014	.01775
	n_{cl}	13.1	6	2	7	4	1	.52
	n_{vl}	13	13	13	14	12	10	14
	n_2	2	2	2	2	4	19	1
12-24	$\overline{X}$	7.06	33.04	59.90	38.54	35.61	1.78	.6416
	EMS	19.93	84.84	57.17	87.39	30.15	.01501	.0992

Table 3--Continued

		Soil Properties						
Depth in Inches		Sand	Silt	Clay	Suction .33 Bars	Suction .66 Bars	Bulk Density	Organic Material
	DF	11	11	11	11	11	12	12
	S_1^2	.54	17.27	5.51	24.00	3.75	.00111	.0270
	S_2^2	17.81	16.62	35.40	8.67	15.35	.00961	.02687
	n_{cl}	14	8	1	7	2	11	37
	n_{vl}	5	12	8	14	10	11	12
	n_2	15	3	6	2	6	16	3
24-36	$\overline{X}$	6.70	33.38	59.87	39.88	36.02		.6045
	EMS	51.70	107.11	126.8	36.09	49.76		.170
	DF	7	7	7	7	7		7
	S_1^2	12.89	29.28	19.97	19.97	12.62		.0653
	S_2^2	6.73	5.20	9.19	9.19	5.82		.00866
	n_{cl}	14.2	12	6	6	5		82

Table 3--Continued

		Soil Properties					
Depth in Inches		Sand	Silt	Clay	Suction .33 Bars	Suction .66 Bars	Bulk Density	Organic Material
	n_{v1}	13	14	14	14	14		15
	n_2	2	1	2	2	2		1

Table 4. Means, Estimated Mean Squares, Variance Components, and Solutions to the Optimum Allocation Problem for Soil Physical Properties on Watershed 6

		Soil Properties						
Depth in Inches		Sand	Silt	Clay	Suction .33 Bars	Suction .66 Bars	Bulk Density	Organic Material
0-3	$\overline{X}$	0.19	50.339	39.59	28.33	24.16	1.78	1.0763
	EMS	56.03	68.71	418.58	38.65	31.04	.05361	.2608
	DF	13	13	13	13	13	13	13
	S_1^2	14.90		140.05	8.50	8.67	.01623	.07763
	S_2^2	12.37	85.58	8.23	13.75	6.34	.00606	.05036
	n_{c1}	75		38	6	7	2	34
	n_{v1}	12		15	17	13	15	13
	n_2	2		1	4	3	3	2
	RE	1.360	1.214	1.478	.9743		.97	.77
3-6	$\overline{X}$	7.45	37.47	54.29	29.95	25.97	1.71	.7959
	EMS	31.53	197.20	368.07	60.60	30.68	.0384	.2738
	DF	13	13	13	13	13	13	13

Table 4--Continued

		Soil Properties						
Depth in Inches		Sand	Silt	Clay	Suction .33 Bars	Suction .66 Bars	Bulk Density	Organic Material
	S_1^2	7.33	58.96	82.97	12.98	8.33	.01148	.08593
	S_2^2	9.55	20.32	137.14	22.57	6.28	.00396	.01598
	n_{c1}	73	20	16	8	6	2	62
	n_{v1}	12	14	11	12	13	15	14
	n_2	3	1	3	4	3	3	1
6-12	$\overline{X}$	7.19	40.83	50.88	32.13	29.03	1.78	.5510
	EMS	25.16	191.38	468.71	58.50	76.66	.03516	.0732
	DF	13	13	13	13	13	13	13
	S_1^2	3.65	58.19	150.19	18.68	24.48	.01111	.01985
	S_2^2	14.47	20.87	18.15	3.76	3.23	.00184	.01664
	n_{c1}	48	14	25	8	12	1	38
	n_{v1}	9	14	147	15	15	16	12
	n_2	5	2	1	1	1	2	2

Table 4--Continued

		Soil Properties						
Depth in Inches		Sand	Silt	Clay	Suction .33 Bars	Suction .66 Bars	Bulk Density	Organic Material
12-24	$\overline{X}$	7.69	35.76	55.35	33.83	31.74	1.84	.437
	EMS	43.57	111.62	267.81	52.36	64.62	.00748	.0372
	DF	13	13	13	13	13	13	13
	S_1^2	11.81	29.18	81.07	14.36	14.78	.00117	.00569
	S_2^2	8.13	24.06	24.59	9.29	21.32	.00397	.02099
	n_{cl}	102	12	12	6	8	1	24
	n_{vl}	13	12	14	13	371	13	10
	n_2	2	2	1	3	1	10	5
24-36	$\overline{X}$	11.092	32.444	56.848	37.3583	35.752		.2850
	EMS	138.77	90.22	244.82	20.55	55.85		.0314
	DF	12	12	12	12	12		11
	S_2^2	13.53	119.46	84.44	26.29	8.77		.02242

Table 5. Means, Estimated Mean Squares, Variance Components, and Solutions to the Optimum Allocation Problem for Soil Physical Properties on Watershed 9

		Soil Properties						
Depth in Inches		Sand	Silt	Clay	Suction .33 Bars	Suction .66 Bars	Bulk Density	Organic Material
0-3	$\bar{X}$	20.36	51.33	28.33	28.33	25.37	1.80	2.6132
	EMS	194.40	87.86	66.41	18.86	46.65	.03183	6.311
	DF	49	49	49	49	49	49	49
	S_1^2	64.40	14.80	15.71	3.18	10.44	.0063	2.06197
	S_2^2	6.36	44.64	20.53	10.09	17.84	1.01406	.1254
	n_{cl}	67	4	11	2	9	2	127
	n_{vl}	15	10	12	11	12	5	15
	n_2	1	4	3	6	4	70	1
	RE	.857	.349	.956	1.0725		.40	.65
3-6	$\bar{X}$	18.43	48.0683	33.54	26.8863	24.42	1.66	1.6347
	EMS	104.76	54.50	137.70	22.82	29.28	.0343	.1710
	DF	49	49	49	49	49	49	49
	S_1^2	25.51		37.05		7.32	.00885	

Table 5--Continued

Depth in Inches		Sand	Silt	Clay	Suction .33 Bars	Suction .66 Bars	Bulk Density	Organic Material
	S_2^2	32.24	78.89	32.45	24.73	8.48	.00918	.6728
	n_{cl}	42		17		6	1	
	n_{vl}	12		12		13	14	
	n_2	3		2		3	6	
6-12	$\overline{X}$	16.62	42.32	40.68	30.20	28.37	1.80	1.0477
	EMS	133.40	168.38	216.81	147.31	263.19	.04586	.2911
	DF	47	47	47	47	47	47	47
	S_1^2	32.34	39.87	64.28	41.53	32.29	.0146	.04284
	S_2^2	40.59	53.94	32.33	36.12	26.73	.00599	.0773
	n_{cl}	65	12	12	23	20	2	23
	n_{vl}	12	11	12	13	13	15	11
	n_2	3	3	2	3	3	4	4

Table 5--Continued

Depth in Inches		Sand	Silt	Clay	Suction .33 Bars	Suction .66 Bars	Bulk Density	Organic Material
		Soil Properties						
12-24	$\bar{X}$	13.92	32.21	54.98	43.95	39.02	1.86	.7409
	EMS	136.07	241.71	245.53	375.96	263.19	.030748	.0657
	DF	37	37	37	36	37	37	37
	S_1^2	39.07	64.20	68.45	145.14	83.98	.00962	.0112
	S_2^2	32.53	71.58	64.13	37.77	40.63	.00526	.0358
	n_{cl}	105	34	12	34	26	1	13
	n_{vl}	12	12	12	14	14	15	10
	n_2	2	3	2	2	2	4	5
24-36	$\bar{X}$	17.6135	27.1567	54.9864	47.5944	43.6675		.5823
	EMS	135.85	142.26	223.29	415.22	203.54		.0994
	DF	17	17	17	16	17		17
	S_2^2	73.72		66.16	21.48	56.96		

Table 6. Means, Estimated Mean Squares, Variance Components, and Solutions to the Optimum Allocation Problem for Soil Physical Properties on Watershed 11

Depth in Inches		Soil Properties						
		Sand	Silt	Clay	Suction .33 Bars	Suction .66 Bars	Bulk Density	Organic Material
0-3	$\bar{X}$	12.77	51.78	35.06	28.76	25.04	1.61	1.5939
	EMS	33.49	122.93	172.85	40.80	64.43	.0556	.3726
	DF	19	19	19	19	19	19	19
	S_1^2	4.25	31.41	48.43	12.09	17.25	.00724	.06529
	S_2^2	20.94	30.25	29.98	9.98	15.54	.03124	.1898
	n_{c1}	19	6	20	7	14	1	16
	n_{v1}	9	12	13	13	13	12	10
	n_2	6	2	2	3	3	11	5
	RE	1.77	.970	1.048	1.0725		1.05	1.01
3-6	$\bar{X}$	10.07	46.93	43.34	29.37	26.09	1.54	.9693
	EMS	26.91	163.00	145.66	40.82	51.43	.0209	.2063
	DF	19	19	19	19	19	19	19

Table 6--Continued

		Soil Properties						
Depth in Inches		Sand	Silt	Clay	Suction .33 Bars	Suction .66 Bars	Bulk Density	Organic Material
	S_1^2	6.03	47.25	22.90	10.79	13.71	.00393	.05783
	S_2^2	8.83	21.24	76.94	11.70	13.04	.00910	.0328
	n_{cl}	34	10	8	6	10	1	31
	n_{vl}	11	13	10	12	13	13	13
	n_2	3	2	5	3	3	8	2
6-12	$\overline{X}$	7.6118	39.70	52.20	32.90	30.26	1.64	.6774
	EMS	10.35	148.33	227.00	39.29	81.90	.0209	.0679
	DF	19	19	19	19	19	19	19
	S_1^2	12.46	38.20	57.66	9.53	23.65	.00393	.01537
	S_2^2		35.64	56.89	14.61	15.66	.00910	.02257
	n_{cl}		13	11	5	13	1	20
	n_{vl}		12	12	12	13	13	11
	n_2		2	3	3	3	8	3

Table 6--Continued

		Soil Properties						
Depth in Inches		Sand	Silt	Clay	Suction .33 Bars	Suction .66 Bars	Bulk Density	Organic Material
12-24	$\bar{X}$	7.10	31.81	58.22	37.9333	35.01	1.61	.4556
	EMS	156.04	78.53	350.79	25.38	51.49	.02723	.0142
	DF	19	19	19	18	19	18	19
	S_1^2	53.68	29.45	117.73		12.61	.00735	
	S_2^2	8.97	22.50	28.20	27.16	17.45	.00517	.01704
	n_{cl}	475	11	16		5	1	
	n_{vl}	14	12	14		12	14	
	n_2	1	3	1		4	5	
24-36	$\bar{X}$	14.3280	28.532	57.180	40.9800	40.0833		.4556
	EMS	182.21	29.24	163.72	97.84	70.06		.0481
	DF	17	17	17	13	15		16

Table 7. Means, Estimated Mean Squares, and Variance Components of the Soil Physical Properties of the Gem Soil Series on Watershed 6

		Soil Properties						
Depth in Inches		Sand	Silt	Clay	Suction .33 Bars	Suction .66 Bars	Bulk Density	Organic Material
0-3	$\overline{X}$	7.9739	45.8826	46.3217	.3045	.2586	1.6804	1.0160
	EMS	26.8761	190.2761	263.0925	.0021	.0022	.0659	.2724
	DF	7	7	7	7	7	7	7
	S_1^2	4.6144	61.9777	88.3498	.00003	-.0050	.0205	.0991
	S_2^2	13.6327	12.4000	9.5287	.0020	.0151	.0071	.02566
3-6	$\overline{X}$	4.9541	41.1708	53.8833	.3312	.2859	1.7775	.6826
	EMS	3.8257	38.7109	35.1048	.0019	.0003	.0135	.0981
	DF	7	7	7	7	7	7	7
	S_1^2	1.9056	9.5925	6.1862	-.0006	.0002	.0034	.0256
	S_2^2	9.5425	9.9333	16.5462	.0035	.0010	.0033	.0247
6-12	$\overline{X}$	6.0958	36.4500	57.5291	.3436	.3096	1.8334	.5043
	EMS	21.1757	38.2505	35.3613	.003	.0008	.0021	.0515
	DF	7	7	7	7	7	7	7

Table 7--Continued

Depth in Inches		Sand	Silt	Clay	Suction .33 Bars	Suction .66 Bars	Bulk Density	Organic Material
				Soil Properties				
	S_1^2	1.7298	4.1492	3.3113	.00003	.0002	-.0007	.0099
	S_2^2	15.9862	25.8029	25.4272	.0002	.0003	.0040	.0230
12-24	$\overline{X}$	6.9875	35.9000	57.4375	.3479	.3118	1.8691	.4759
	EMS	56.8219	73.4409	25.7871	.0009	.0013	.0026	.0306
	DF	7	7	7	7	7	7	7
	S_1^2	15.5833	15.2259	3.6365	.0001	.0003	-.0001	.0119
	S_2^2	10.0720	27.7633	36.6966	.0006	.0005	.0030	.0001

Table 8. Mean, Estimated Mean Squares, and Variance Components of the Soil Physical Properties of Springerville Soil Series on Watershed 6

		Soil Properties						
Depth in Inches		Sand	Silt	Clay	Suction .33 Bars	Suction .66 Bars	Bulk Density	Organic Material
0-3	$\bar{X}$	11.1000	53.8833	35.0833	.2643	.2292	1.5341	1.1333
	EMS	38.7933	69.0344	20.9566	.0031	.0071	.0093	.4365
	DF	3	3	3	3	3	3	3
	S_1^2	11.5311	20.8559	65.9728	.0008	.0022	.0014	.1138
	S_2^2	4.2000	6.4666	6.0383	.0007	.0008	.0052	.0951
3-6	$\bar{X}$	8.3083	49.9916	41.2666	.2720	.2413	1.6500	.9316
	EMS	145.9119	119.4986	396.9600	.0014	.0039	.0418	.2679
	DF	3	3	3	3	3	3	3
	S_1^2	11.1266	43.3675	30.5108	.0004	.00015	.0037	.0092
6-12	$\bar{X}$	8.9250	48.0250	43.3750	.2888	.2511	1.7191	.6391
	EMS	38.7933	234.4808	357.7875	.0079	.0089	.0784	.1480
	DF	3	3	3	3	3	3	3

Table 8--Continued

		Soil Properties						
Depth in Inches		Sand	Silt	Clay	Suction .33 Bars	Suction .66 Bars	Bulk Density	Organic Material
	S_1^2	9.0606	72.3378	93.2292	.0025	.0024	.0246	.0439
	S_2^2	11.6116	17.4675	78.1000	.0004	.0018	.0048	.0134
12-24	$\overline{X}$	8.9000	34.4083	51.6916	.2965	.2900	1.7975	.3900
	EMS	38.3511	132.9079	313.2919	.0052	.0065	.0128	.0211
	DF	3	3	3	3	3	3	3
	S_1^2	11.4843	41.0057	100.7101	.0012	.0013	.0018	-.0004
	S_2^2	3.8983	9.8925	11.16116	.0015	.0025	.0073	-.0004
24-36	$\overline{X}$	7.8416	34.5750	58.3916	.3619	.3500	1.8633	.2375
	EMS	6.8331	165.4097	168.7963	.0009	.0049	.0013	.0132
	DF	3	3	3	3	3	3	3
	S_1^2	-1.1740	-3.0789	15.6513	-.0086	.0016	-.0001	.0009
	S_2^2	10.3550	174.6466	121.8425	.0035	.0001	.0016	-.0104

Table 9. Means, Estimated Mean Squares, and Variance Components of the Soil Physical Properties of the Sponseller Soil Series on Watershed 9

		Soil Properties						
Depth in Inches		Sand	Silt	Clay	Suction .33 Bars	Suction .66 Bars	Bulk Density	Organic Material
0-3	$\overline{X}$	20.196	51.9880	27.8160	.2899	.2499	1.14341	2.8226
	EMS	132.9037	114.7474	88.8167	.0022	.0050	.0562	5.8203
	DF	8	8	8	8	8	8	8
	S_1^2	84.0175	8.3943	12.6577	.00055	.00068	.0180	.4007
	S_2^2	48.8862	91.4954	53.7550	.0007	.0032	.0072	1.8818
3-6	$\overline{X}$	16.6375	50.6416	33.0916	.27773	.2499	1.4808	1.7687
	EMS	54.8880	157.0075	223.6393	.0029	.0050	.0405	2.3175
	DF	8	8	8	8	8	8	8
	S_1^2	13.1041	53.4049	77.8057	.0097	.0068	.0126	.8217
	S_2^2	19.8714	14.9505	16.6762	.0026	.0032	.0056	.1371
6-12	$\overline{X}$	14.9041	45.3916	40.0791	.3097	.3072	1.5833	
	EMS	103.2642	324.6816	454.7028	.0303	.0064	.0403	

Table 9--Continued

		Soil Properties						
Depth in Inches		Sand	Silt	Clay	Suction .33 Bars	Suction .66 Bars	Bulk Density	Organic Material
	DF	7	7	7	7	7	7	
	S_1^2	22.8358	44.3279	58.0312	.0217	.0022	.0139	
	S_2^2	34.7487	93.4512	133.2239	.0022	.0008	.0044	
12-24	$\overline{X}$	18.84	28.08	53.08	.3857	.3802	1.582	.6990
	EMS	68.1574	474.0197	466.177	.0615	.0323	.0301	.2056
	DF	3	3	3	3	3	3	3
	S_1^2	-8.7238	181.2592	181.5126	.0217	.0108	.0081	.0664
	S_2^2	89.7052	26.3094	42.4508	.0022	.0028	.0102	.0416

Table 10. Means, Estimated Mean Squares, and Variance Components of the Soil Physical Properties of the Siesta Soil Series on Watershed 9

		Soil Properties						
Depth in Inches		Sand	Silt	Clay	Suction .33 Bars	Suction .66 Bars	Bulk Density	Organic Material
0-3	$\bar{X}$	22.7454	50.8242	26.4909	.2910	.2671	1.3500	2.2243
	EMS	108.8108	67.8573	53.9533	.0087	.0075	.0922	1.4948
	DF	10	10	10	10	10	10	10
	S_1^2	29.9983	18.6869	15.5679	.0025	.0019	.0221	.1997
	S_2^2	18.8160	11.7966	7.2496	.0018	.0024	.0302	.9517
3-6	$\bar{X}$	19.5272	49.8393	30.5393	.2490	.2349	1.4860	1.868
	EMS	117.6345	59.2058	122.7212	.0259	.0019	.0441	2.2837
	DF	10	10	10	10	10	10	10
	S_1^2	27.4994	4.9780	33.3269	.0085	.0005	.0125	.7357
	S_2^2	35.1363	44.2718	22.7403	.0012	.0003	.0067	.1429
6-12	$\bar{X}$	19.9322	44.1870	35.8806	.2771	.2543	1.5646	1.0526
	EMS	147.9347	152.5643	111.4650	.0616	.0047	.0736	.2046

Table 10--Continued

Depth in Inches		Soil Properties						
		Sand	Silt	Clay	Suction .33 Bars	Suction .66 Bars	Bulk Density	Organic Material
	DF	10	10	10	10	10	10	10
	S_1^2	35.9417	37.8792	32.6643	.0220	.0008	.0223	.0513
	S_2^2	47.2980	46.6025	20.0049	.0017	.0024	.0129	.0650
12-24	$\overline{X}$	16.1958	37.4541	46.2333	.3645	.2960	1.6500	.7683
	EMS	127.2489	295.0742	521.6561	.2426	.0141	.0304	.0565
	DF	10	10	10	10	10	10	10
	S_1^2	32.7241	70.4702	154.6704	.0907	.0033	.0091	-.0073
	S_2^2	29.0766	83.6637	57.6450	.0060	.0059	.0055	.0784

Table 11. Means, Estimated Mean Squares, and Variance Components of the Soil Physical Properties of the Brolliar Soil Series on Watershed 9

		Soil Properties						
Depth in Inches		Sand	Silt	Clay	Suction .33 Bars	Suction .66 Bars	Bulk Density	Organic Material
0-3	$\bar{X}$	18.7836	57.0508	29.1639	.2777	.2437	1.4454	2.3038
	EMS	76.3522	70.3030	61.9067	.032	.0038	.0316	2.6365
	DF	20	20	20	20	20	20	20
	S_1^2	10.8604	11.9756	17.2633	.0009	.0094	.0084	.8186
	S_2^2	44.8569	35.5737	11.8431	.0007	.0012	.0081	.2215
3-6	$\bar{X}$	17.9683	47.1183	34.9116	.2662	.2361	1.5835	1.4530
	EMS	67.8641	46.2945	154.5741	.0055	.0033	.0210	.6419
	DF	20	20	20	20	20	20	20
	S_1^2	15.0734	76.7007	44.8427	.0011	.00093	.0048	.0955
6-12	$\bar{X}$	15.7266	41.6150	43.3250	.2914	.2757	1.6592	.9781
	EMS	117.0760	102.8966	241.4806	.0145	.0102	.0275	.1336
	DF	19	19	19	19	19	19	19
	S_1^2	19.3618	12.7212	60.9938	.0040	.0024	.0082	.0369

Table 11--Continued

		Soil Properties						
Depth in Inches		Sand	Silt	Clay	Suction .33 Bars	Suction .66 Bars	Bulk Density	Organic Material
	S_2^2	58.8693	64.7330	58.4990	.0026	.0030	.0042	.0230
12-24	$\bar{X}$	11.7102	30.8564	57.4076	.4666	.4143	1.7476	.7170
	EMS	98.4464	202.4666	376.5735	.0420	.0303	.0118	.0953
	DF	14	14	14	14	14	14	14
	S_1^2	27.3464	52.7371	119.7607	.4880	.4600	1.7088	.6200
	S_2^2	27.6193	65.8776	66.3932	.0039	.0046	.0044	.0171
24-36	$\bar{X}$	17.4176	26.1529	56.4294	.4880	.4600	1.7088	.6200
	EMS	129.6716	293.2871	303.4684	.0876	.0407	.0118	.0154
	DF	5	5	5	5	5	5	5
	S_1^2	42.4958	88.8663	80.5222	.0323	.0129	.0027	.0042
	S_2^2	9.8333	42.6842	76.3957	.0019	.0066	.0043	.0036

Table 12. Means, Estimated Mean Squares, and Variance Components of the Soil Physical Properties of the Gem Series on Watershed 11

Depth in Inches		Soil Properties: Sand	Silt	Clay	Suction .33 Bars	Suction .66 Bars	Bulk Density	Organic Material
0-3	$\bar{X}$	11.6393	51.9464	36.4212	.2861	.2476	1.5427	1.5576
	EMS	23.3572	120.5675	184.8395	.0027	.0027	.0104	.3745
	DF	10	10	10	10	10	10	10
	S_1^2	4.1781	32.3406	53.4341	.006	.007	.0004	.0773
	S_2^2	10.8230	23.5457	24.5372	.0011	.0006	.0116	.1502
3-6	$\bar{X}$	9.5969	45.5393	43.8666	.2913	.260	1.6739	.9342
	EMS	32.2408	118.7778	21.8906	.0037	.0034	.0205	.0938
	DF	10	10	10	10	10	10	10
	S_1^2	9.1094	28.9399	-1.1908	.0001	.0001	.0032	.0185
	S_2^2	4.9121	31.9581	25.4630	.0009	.0030	.0110	.0383
6-12	$\bar{X}$	7.1437	38.8281	53.0906	.3262	.0390	1.8021	.6162
	EMS	10.1727	161.9684	259.2275	.0039	.0097	.0164	.0479

Table 12--Continued

Depth in Inches		Sand	Silt	Clay	Suction .33 Bars	Suction .66 Bars	Bulk Density	Organic Material
		Soil Properties						
	DF	10	10	10	10	10	10	10
	S_1^2	-.0073	44.5313	62.2602	.0004	.0032	.0043	.0108
	S_2^2	10.1938	32.8276	78.6729	.0014	.0008	.0036	.0167
12-24	$\overline{X}$	6.2703	34.1740	58.4259	.3768	.3449	1.8760	.4493
	EMS	102.4810	35.6802	148.0050	.0044	.0060	.0011	.0168
	DF	9	9	9	9	9	9	9
	S_1^2	35.9422	-.1569	39.4546	.0014	.0014	.00003	.0010
	S_2^2	5.7966	36.1264	41.8721	.0009	.0025	.0010	.0140

Table 13. Means, Estimated Mean Squares, and Variance Components of the Soil Physical Properties of the Brolliar Soil Series on Watershed 11

		Soil Properties						
Depth in Inches		Sand	Silt	Clay	Suction .33 Bars	Suction .66 Bars	Bulk Density	Organic Material
0-3	$\overline{X}$	14.4884	51.5615	34.0653	.2895	.2581	1.5715	1.6425
	EMS	25.1491	140.9843	181.9448	.0062	.2135	.0610	.4050
	DF	8	8	8	8	8	8	8
	S_1^2	-2.6776	35.4336	49.9727	.0023	.0769	-.1025	.2453
	S_2^2	32.8607	38.9356	38.0235	.0007	.0004	.3563	.2453
3-6	$\overline{X}$	10.2925	47.4037	41.9481	.2967	.2594	1.6396	1.0511
	EMS	26.7914	237.2787	282.1084	.0049	.2055	.0218	.2295
	DF	8	8	8	8	8	8	8
	S_1^2	3.5133	76.3825	90.2736	.0014	.0772	.0051	-.0812
	S_2^2	16.2514	8.1311	11.2877	.0014	.0009	.0066	.4633
6-12	$\overline{X}$	8.1666	40.7259	51.1370	.3321	.2944	1.7848	.7500
	EMS	16.9308	13.2398	208.1220	.0043	.2779	.0410	.0694

Table 13--Continued

		Soil Properties						
Depth in Inches		Sand	Silt	Clay	Suction .33 Bars	Suction .66 Bars	Bulk Density	Organic Material
	DF	8	8	8	8	8	8	8
	S_1^2	1.6467	34.7716	58.8857	.0007	.118	.0115	.0134
	S_2^2	11.9907	38.9251	31.4648	.0024	.2452	.0066	.0293
12-24	$\overline{X}$	6.0037	30.1481	63.8851	.3820	.3601	1.8466	.4500
	EMS	13.3828	73.0292	44.1675	.0006	.4404	.0118	.0119
	DF	8	8	8	8	8	8	8
	S_1^2	.4719	21.1314	9.3193	-.0007	.1465	.0017	.0026
	S_2^2	11.9670	9.6351	16.2096	.0024	.0010	.0169	.0196

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SECTION 6

INFILTRATION CHARACTERISTICS OF SOILS IN THE BEAVER CREEK AREA OF NORTH CENTRAL ARIZONA

by

John Raymond Rector

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INTRODUCTION

The amount of precipitation that goes into surface runoff, subsurface flow, base flow or deep recharge on a watershed is largely determined by the hydrologic characteristics of the soil. Infiltration, the entry into the soil of water available at the soil surface, is one of the most important of these characteristics. It is controlled by the size and geometry of the exceedingly complex flow paths through the soil media.

Because of this complexity the infiltration phenomena must be described by a lumped coefficient approach, analogous to the manner groundwater flows are described using the lumped coefficient, hydraulic conductivity, in the Darcy equation. Since soil geometry is some complex function of soil physical properties, it follows that infiltration coefficients would be parametric functions involving these properties. In this study an attempt is made to develop empirical relationships between infiltration parameters and the physical properties of soils on the experimental watersheds operated by the U. S. Forest Service in the Beaver Creek Area of Arizona.

Objectives

1. To determine the infiltration characteristics of several soils on experimental watersheds in the Beaver Creek Area.

2. To develop functional relationships between infiltration parameters and the physical properties of these soils which may be used for prediction purposes.

Scope

The study was made on data collected with a double ring infiltrometer on Beaver Creek watersheds 3, 6, 9, and 11. Infiltration runs were made on these watersheds during the summer of 1968 after the soils had been wetted by seasonal rains. Data was collected at 33 of the soil sampling points described in A Study to Determine the Hydrologic and Physical Properties of some Beaver Creek Soils (1968). However, because of the inaccessibility of some of the sample points, the infiltration runs could not be completely randomized. Saturated hydraulic conductivity was determined on undisturbed soil cores taken from the 0 to 3 inch soil layer at all sample points at the time infiltration runs were made.

LITERATURE REVIEW

The main aim in compiling the literature review has been to cover those articles which have a direct bearing on the study rather than all aspects of infiltration. The literature review deals with the most frequently used infiltration equations and with the effects of some factors pertinent to this study on the infiltration phenomena.

Infiltration Equations

Kostrahov (1932) apparently was the first to suggest the frequently used infiltration equation:

$$i = Ct^B \qquad (1)$$

where C and B are constants and i is the accumulated quantity of inflow at time t.

The best known infiltration equation is that attributed to Horton (1942) but was first proposed by Gardner and Widstoe (1921). The integral form of this equation is:

$$i = f_c t + \frac{f_o - f_c}{K} - \left(\frac{f_o - f_c}{K}\right) \exp(-Kt) \qquad (2)$$

where f_o is the initial infiltration capacity, f_c the final infiltration capacity and K is a constant.

These equations are empirical, and attempts at fitting them to actual data have been only moderately successful. The first successful attempt to develop an infiltration equation in terms of basic physical properties of the system has been made by Philip (1957a). His equation stems from the general equation for flow of a liquid in a homogeneous porous medium of stable structure. The flow equation may be written in cartisean coordinates for the Z direction as

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} \left(D_{(\theta)} \frac{\partial \theta}{\partial z} \right) - \frac{\partial K}{\partial z} \tag{3}$$

where θ is the volumetric water content, t is time, and K is the hydraulic conductivity.

Philip's solution of equation (3) subject to the boundary conditions

$$\begin{aligned} \theta &= \theta_{initial} , \quad t = 0 , \quad x \quad 0 \\ \theta &= \theta_{sat} , \quad x = 0 , \quad t \quad 0 \end{aligned} \tag{4}$$

is the following power series in t:

$$\begin{aligned} x = \phi(\theta)\, t^{1/2} + \chi(\theta)\, t + \psi(\theta)\, t^{3/2} + W(\theta)\, t^2 + \\ \ldots + f_m(\theta)\, t^{m/2} + \ldots \end{aligned} \tag{5}$$

where the coefficients $\phi(\theta)$, $\chi(\theta)$, $\psi(\theta)$, $W(\theta) \ldots, f_m(\theta)$ are functions of θ and are the solutions of a series of ordinary

differential equations which can be solved by numerical methods.

The total infiltration i may be obtained from this series since the total change in water content in a column of soil equals the difference between the time integral of the flux at $x = 0$ and at infinity

$$i = \int_{\theta_{in.}}^{\theta_{sat.}} x \, d\theta + K_{in} t \qquad (6)$$

Integrating equation (6) with respect to θ gives

$$\int_{\theta_{in.}}^{\theta_{sat.}} x \, d\theta = t^{1/2} \int_{\phi} + t \int_{x} + t^{3/2} \int_{\psi} + t^{2} \int_{w} +$$

$$\ldots + t^{m/2} \int_{f_m} + \ldots \qquad (7)$$

Using equation (7) in equation (6) gives

$$i = t^{1/2} \int_{\phi} + t(K_{in.} + \int_{x}) + t^{3/2} \int_{\psi} + t^{2} \int_{w} +$$

$$\ldots. + t^{m/2} \int_{f_m} + \ldots \qquad (8)$$

Equation (8) converges rapidly for all except very long t. Ignoring the last terms, Philip gives an approximate infiltration equation as

$$i = St^{1/2} + At \qquad (9)$$

where

$$S = \int_{\phi}$$

and

$$A = K_{in.} + \int_{x} .$$

The differential of equation (9) gives the infiltration capacity I as

$$I = \frac{S}{2t^{1/2}} + A \qquad (10)$$

Factors Affecting Infiltration Characteristics

Initial Water Content

The depressing influence of initial soil water content on infiltration is well established in the literature (Tisdall, 1951; Musgrave, 1955; Free, Browning and Musgrave, 1940). The fact that increased initial water content increases the rate of advance of the wetting front has also been observed (Bodman and Colman, 1944; Harris and Turpin, 1917). These apparently contridictory results are due to the effect of the initial water content.

The classical work of Bodman and Colman (1944) offered one of the first valid explanations of this paradox. They regarded the lowered potential gradients in initially moist soils as especially important in reducing infiltration and suggested that the reverse effect on the advance

of the wetting front might be the result of a downward displacement of some of the comparatively mobile water initially present in the moist soil. Thus, the more rapid advance of the wetting front in moist soils attributed to the greater concentration of water molecules near the wet front which originally formed part of the initial water at points higher in the soil. Philip (1957b) points out that this explanation is correct insofar as wet soils versus dry soils is concerned, but states that it is doubtful "if attempts to discern one-to-one causal relationship between various aspects of physical phenomena of this complexity can ever meet with success."

Philip (1957b) solved the problem of the effect of the initial water content on infiltration for the specific example of yolo light clay.

As shown in Figure 1, there is a marked dependence of infiltration on the initial water content for early times. At large times the dependence of the initial water content becomes less important. The tendency for the different curves to become parallel with increasing time indicates that all curves have the line $V_o = K_o$ as asymptote as t increases without limit. Thus, at short times dry and moist soils infiltration is governed by the capacity of the soil to absorb water. Philip calls this term "sorptivity" which will be discussed in a later section. At large times and for initially wet soils the infiltration rates approach the hydraulic conductivity.

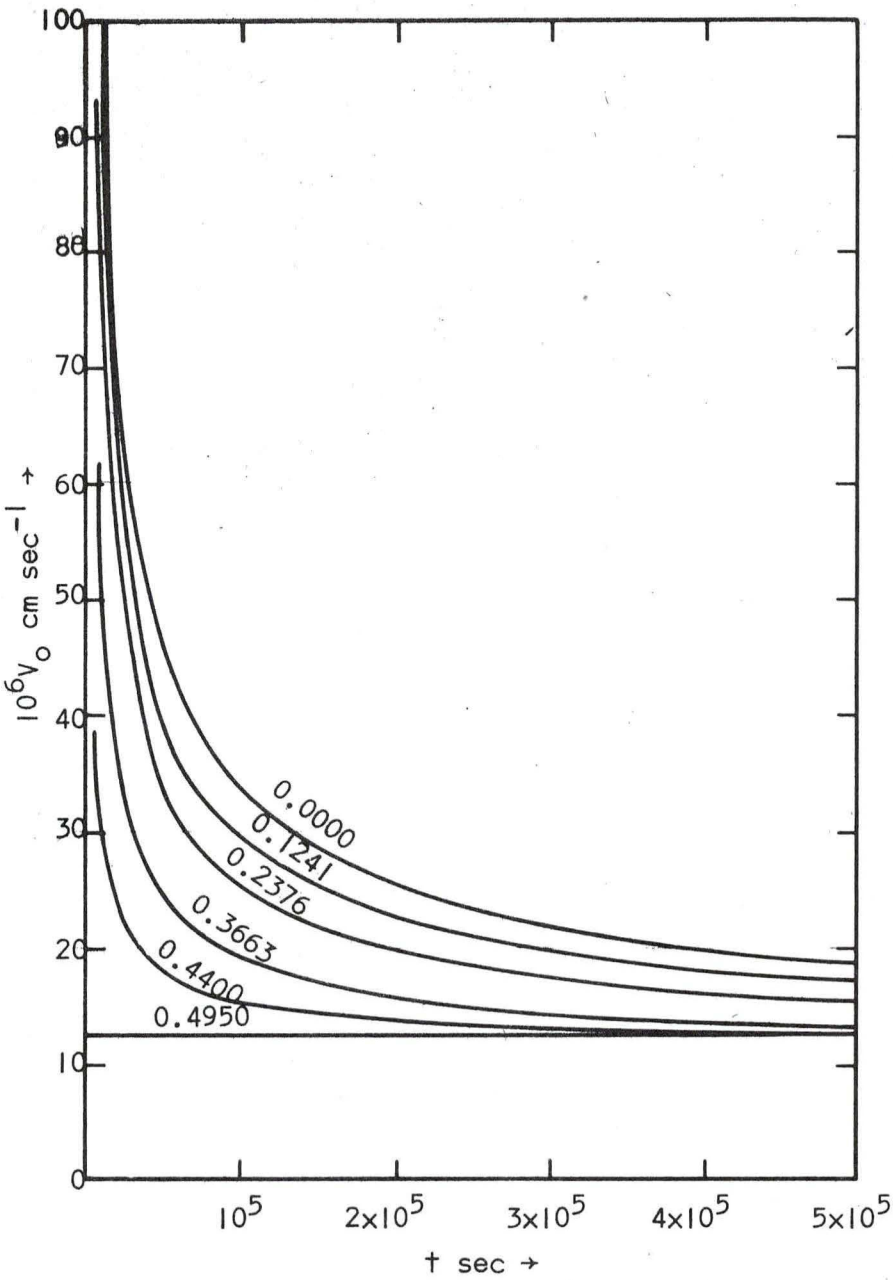

Figure 1. Influence of initial moisture content on infiltration rate Computed for Yolo light clay (Philip, 1957b)

Temperature

Moore (1941) found that as water temperature increased between 5^{o} and $30^{o}C$. there was a corresponding increase in infiltration rate. Bertoni, Larson, and Shrader (1958) observed that final infiltration rates followed seasonal temperature patterns very closely. These results are in accord with the findings of earlier investigators (Beutner, Baebe, and Horton, 1940; Borst, McCall, and Bell, 1945; and Horner and Lloyde, 1940).

Duley and Domingo (1944) stated that infiltration rates of water at $22^{o}C$. were so nearly the same as those at $4^{o}C$. that no significant differences could be detected. Free, Browning and Musgrave (1940) found a correlation between temperature and infiltration of only .28 . In a multiple correlation with other factors the contribution due to temperature was negligible.

Jackson (1963) concluded that since A in equation (9) is approximately proportional to the saturated hydraulic conductivity it should also be proportional to the inverse of viscosity. Since $S > A$ for small times, the sorptivity term is dominant and infiltration should vary with temperature as $(\frac{\partial}{\eta})^{1/2}$ varies with temperature; ∂ being the surface tension and η the viscosity. Thus, for an initially wet soil or for long times, the temperature effect on infiltration can be evaluated. For example, at normal field temperatures between $70^{o}F$. and $85^{o}F$., the viscosity of water varies only .2043 centipoise and thereafter would exert a negligible effect on infiltration rates.

Air Entrapment

The characteristic decrease in infiltration with time observed by some of the earlier investigators such as Baver (1937) was often attributed to the compression of air in soil pores below the wet zone. Bodman and Coleman (1936) concluded that the effect of reduced air permeability on infiltration due to increased water content was negligible. Wilson and Luntin (1963) found air pressures ahead of the wetting front up to 14 cm. of water during initial phases of infiltration into sealed cylinders of soil. At these higher pressures the flux of water through the larger pores was reduced because of entrapped air. As the wetting front advanced, air was isolated and as a result only a fraction of the total number of pores were active in transmitting water. This added to the tortuosity of the flow paths of the conducting channels and thus reduced the influx rate.

Horton (1940) reported that in Russia, air compression hindered infiltration over large areas under natural rainfall, particularly on flat steppe terrain. Wilson and Luthin (1963) reasoned that for large areas infiltration may be affected, but with cylinder infiltrometers, air is free to escape back to the soil surface and the effect is minimized.

Aggregation

Musgrave (1955) considered degree of aggregation as one of the more important soil characteristics affecting intake of water. Burgy

and Scott (1952), Scott and Burgy (1956) and Scott (1956) found a marked increase in water stable aggregates at 0-1/4 in depths which resulted in appreciable increases in infiltration rates for burned soils as compared to unburned soils. Generally in a soil with a high degree of aggregation, the pore size would be larger and more favorable to infiltration than a nonaggregated soil. This is not always true in practice since the arrangement of aggregates and the degree of intermingling of single grains may actually develop a more dense medium. If aggregates are unstable, continued application of water may reduce porosity and consequently infiltration.

Soil aggregation is often positively correlated with pH. Free, Browning and Musgrave (1940) state that although the absolute pH value is not directly associated with infiltration, the optimum pH value for infiltration should be that at which maximum floculation occurs.

Litter

High infiltration rates are generally associated with a normal litter cover. Once it is removed, infiltration rates under natural or simulated rainfall are reduced. Lawdermilk's (1930) study is often cited as the classic example. He found that surface runoff from plots on which the forest floor had been burned off was 3, 9, and 16.5 times greater than runoff from unburned plots for fine sandy loam, sandy clay loam, and clay loam soils, respectively.

Two infiltrometer studies provide additional evidence. In Arkansas, Arend (1941) found an average infiltration rate of 2.12 inches per hour for unburned plots compared to 1.32 inches per hour for plots that had been burned annually for five or six years. Comparative rates for undisturbed and raked plots were 2.36 and 1.94 inches, respectively. Johnson (1940) found in Colorado that removing the forest floor reduced infiltration capacity from 1.52 to 0.92 inches.

Although the beneficial effects of litter on infiltration is well established, there have been only a few studies designed to determine whether mors or mulls of their variants have different infiltration rates, or to determine what depth of these litter types is critical. Rowe (1940) in California found surface runoff of 5.9, 2.2, 0.5, 0.3 and 0.5 inches for bare soil, and 1/4-, 1/2-, 3/4-, and 1 1/4-inch depths of forest floor, respectively. In this instance, increasing depths beyond 1/2 inch had little or no effect.

The main effect of litter, apparently, as first suggested by Lawdermilk (1930), is to protect the soil surface from rainfall impact and subsequent puddlings. For ring infiltrometers where turbidity is slight, litter depth would be expected to have little influence on infiltration.

Soil Texture and Porosity

Free and Palmer (1940) conducted the most complete investigation to date on the inter-relationships of air pressure, pore size and infiltration. They determined the infiltration rates, penetration rates, and time for complete wetting for a series of open and closed columns, each packed with one of six different size grades of silica sand. Infiltration was related to grade size of sand, and therefore, to the pore size. That is, infiltration rates and penetration rates decreased with decreasing particle sizes. The soil materials used in this study were composed of only sand size particles.

Lutz and Leamer (1939) found that for coarse soil fractions permeability increased exponentially with an increase in particle size. Soils containing high percentages of clay often shrink and swell considerably. When soils swell they do so largely at the expense of soil pores. In this manner large non-capillary pores may become capillary pores and capillary pores may become essentially sealed. Conversely, soil shrinking and cracking increases initial infiltration.

Free, Browning and Musgrave (1940) found no significant effect on infiltration of silt and clay, the two principal volume changing components, in the surface. However, fine fractions in the subsoil were highly correlated with water movement. Lutz and Leamer (1939) reported that the swelling of colloidal material was an important factor

in determining the permeability of the subsoil. Browning (1939) found that for soils having volume changes of less than 20 percent there was only a small effect on infiltration. Infiltration was materially decreased in soils having volume changes above 20 percent. Stirk (1953) found that although cracking associated with shrinking initially increases permeability of a soil, large increases were not found until the water content was reduced considerably below the wilting point. Free, Browning and Musgrave (1940) presented results of infiltration runs on 68 soil profiles ranging in texture from sandy loam to clay. When infiltration rates were ranked it was found that soil textural classification alone was not a good index of infiltration capacity. This is understandable since individual separates within a textural classification may cover a wide range of sizes and may occur in any combination within these ranges. The hydrologic characteristics of possible combinations falling within an arbitrary category may be entirely different. These results point up an inadequacy in the use of the soil survey classification system for describing the hydrologic properties of soils.

METHODS

A general description of the experimental watersheds and the soils on which this study was made is given in A Study to Determine the Hydrologic and Physical Properties of some Beaver Creek Soils (1968). Methods of soils analysis are also given in the same report. A description of the infiltrometer used on the watersheds is given in figure 2. The outer ring (1) was 10.5 inches in diameter and the inner ring (2) 6.5 inches in diameter. Both were made of eight-inch lengths of 1/4-inch well casing, the lower four inches of each were turned down to 1/8 inch thick and the edges tapered. Prior to a run they were forced four inches into the soil with a jack, using the bumper of a truck driven over the site for the insertion.

A 2-cm. head of water was maintained in both rings with Mariotte flasks (3) made from 1000 ml. graduated burets fitted with three glass tubes. Two short tubes (6) were used for filling the burets and permitting air to escape. They were clamped off after each filling. The third tube (4) maintained atmospheric pressure at 2 cm above the soil surface. The flasks were mounted on steel pins driven into the ground. Small pits were dug at the base of each flask to position the atmospheric tube. Outlet tubes (5) were placed over the ring edges, flat on the ground surface below the 2-cm. height.

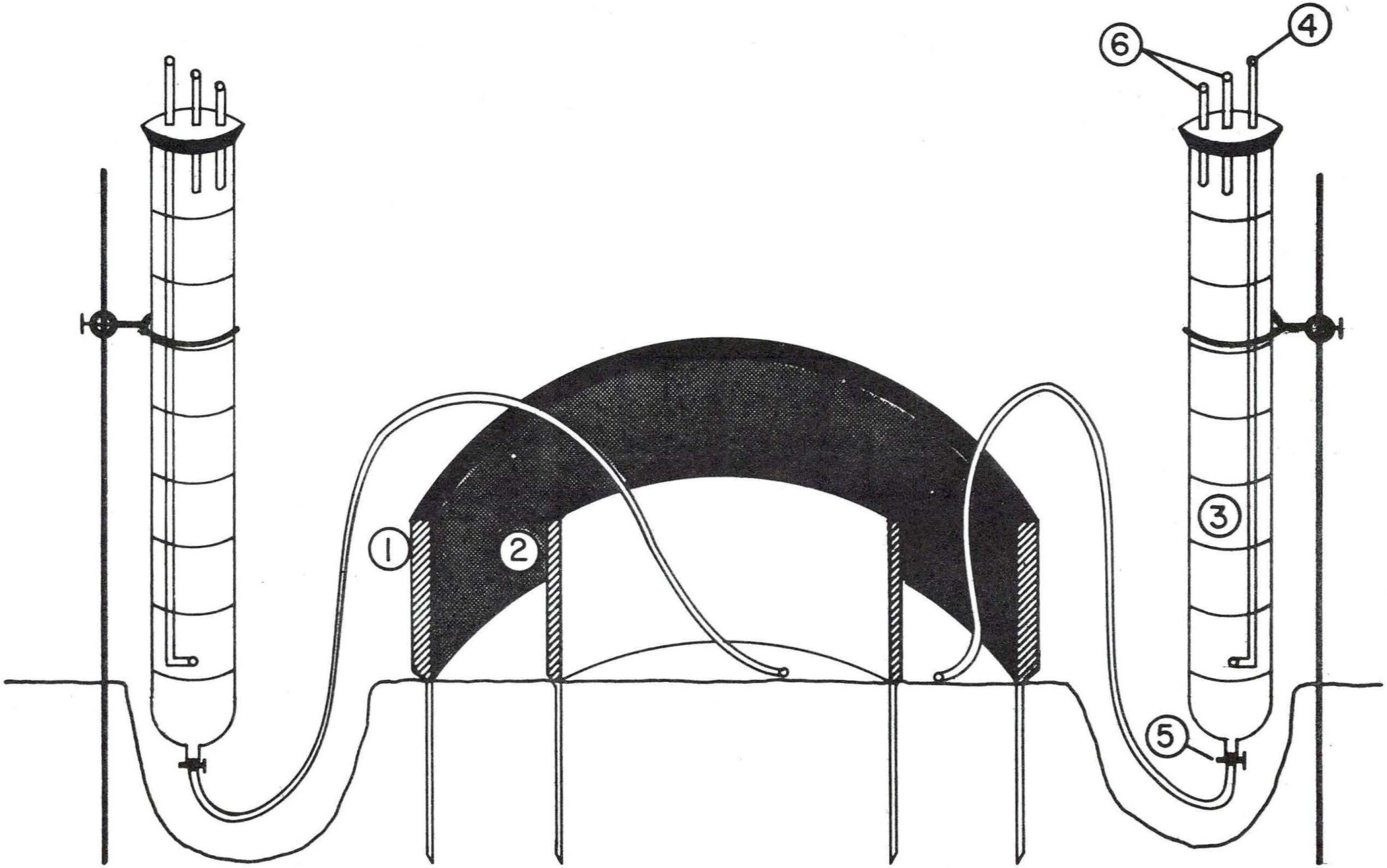

Figure 2. Infiltration Apparatus

To initiate a run, the burets were filled and the outlet tubes removed from the rings. The stopcocks were first opened to allow the outlet tubes to fill with water and then closed. The outlet tubes were then relocated within the rings. Two separate flasks were filled with enough water to bring the water level in each ring to 2 cm; the outer ring requiring 675 ml and the inner ring 427 ml. The water level in the inner ring's buret was then recorded. At zero time the flasks were poured into the respective rings and the stopcocks opened simultaneously. Time readings were then recorded after the entry of each 200 ml of water.

Two replicate infiltration runs were made at each of 33 soil sampling points. Where there was considerable variation between replicates, a third run was made. A total of 81 runs were made in the study.

Cores for measuring hydraulic conductivity were taken with brass rings 4.5 x 5.4 centimeters in diameter driven into the soil. The rings were removed with core intact, sealed in aluminum cans that just fit the sample, and stored in a freezer until ready for measurement.

Hydraulic conductivity measured was with a constant head parameter especially constructed to handle swelling soils and capable of running ten cores simultaneously. (Figure 3) Each of the ten cells of the permeameter consisted of two plexiglas caps (1) with "0" rings (2) to seal the brass sample ring (3). Six layers of screen, sandwiched

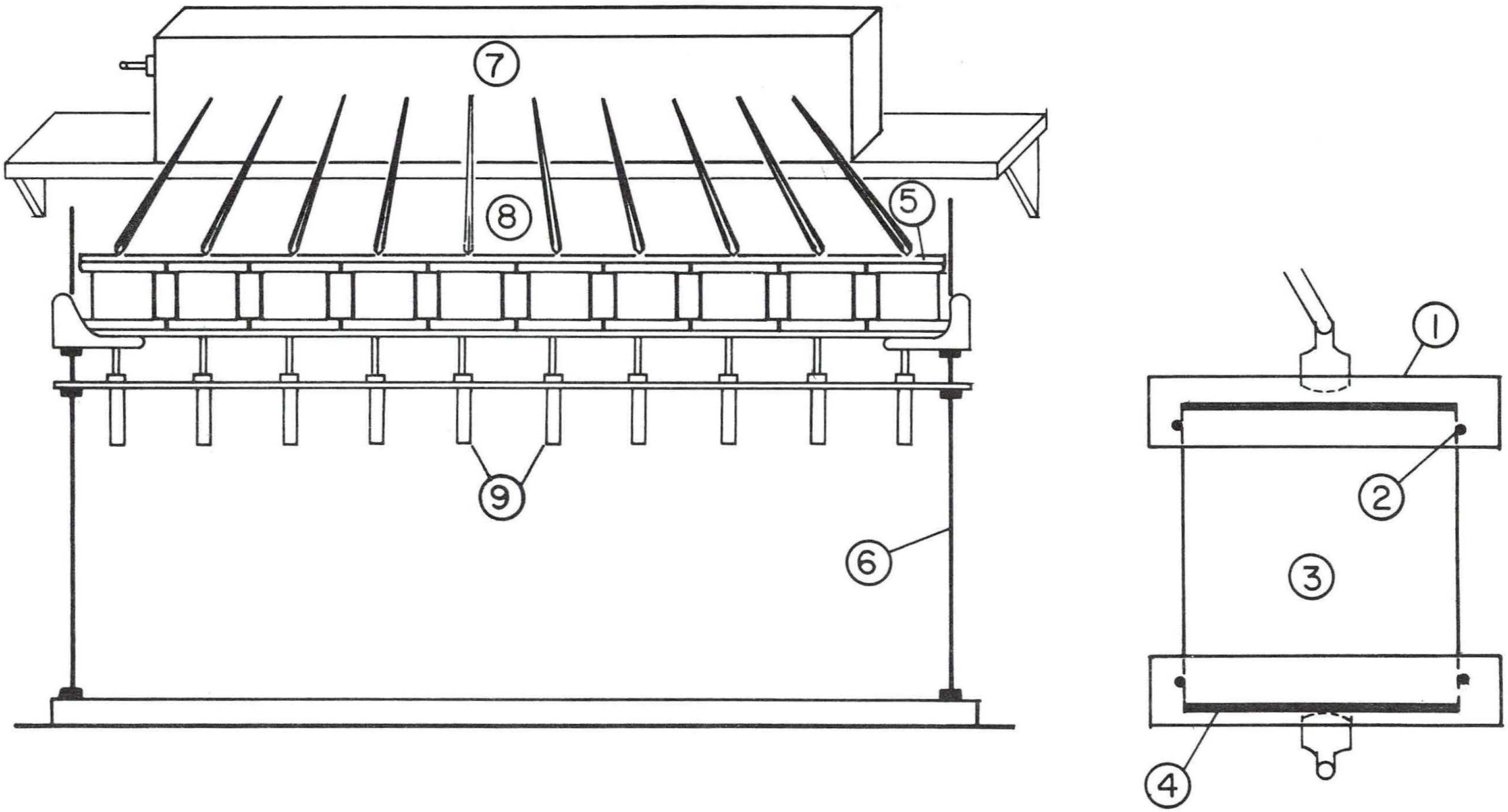

Figure 3. Constant Head Permeameter

between two filter paper disks (4) and fitted into each cap, insured an even distribution of water across the core surface. The assembled cells were mounted in a channel aluminum rack (5) and clamped to contain the sample against swelling pressure. The rack, mounted on two threaded rods (6) beneath the water supply tank (7), could be raised or lowered to control the hydraulic head. A constant water level was maintained in the supply tank by a simple overflow system. Ten polyethylene tubes (8) connected the storage tank to the cells.

Before making a run air was flushed from the cells by inverting the rack and allowing water to flow up through the cores. The rack was left in this position, with the outlet tubes just above the water level in the supply tank, for a period of 24 hours. After this period the rack was again inverted and water was allowed to flow through the cores for two hours before measurements were made. Flow measurements were made by timing out-flow from the cores collected in a bank of tubes below the rack (9). When a measurable quantity of outflow had been obtained, timed and recorded, the tubes were emptied and a new determination begun. Ten determinations were made on each core. Conductivity was determined with the relationship:

$$K = \frac{\overline{L}}{AH} = \frac{\sum_{i=1} Q_L}{\sum_{i=1} t_i} \qquad (11)$$

where K is the conductivity, L, the length of the core, A, the cross sectional area, H the difference in total head, and Q, the quantity of outflow during time, t.

ANALYSIS

In order to test the applicability of Philip's equation, the infiltration data from each run were fitted by multiple linear regression analysis to equation (9), namely:

$$i = St^{1/2} + At .$$

Since at t - 0 i = 0, the regressions were forced through the origin. Equation (9) was found quite suitable and new regressions were made on the combined replicate runs in order to obtain the value of S and A for each sample point. At t = 6000 seconds, infiltration for all runs very nearly approached a constant rate. The infiltration capacity (equivalent to f_c in the Horton equation) was determined at this point with equation (10), namely:

$$I = \frac{S}{2t^{1/2}} + A .$$

Regression Analysis

Regression analyses were used to obtain empirical relationships between the infiltration parameters S, A and I and (1) soil chemical properties, (2) qualitative descriptions of soil profile characteristics

and (3) laboratory measurements of soil physical and hydrologic characteristics. Rational relationships have not been developed that describe the effects of any of the variables in these three sets on infiltration, and preliminary plotting of actual data showed no clear trends. Therefore, only simple first and second order equations were used in the analysis.

The main objective of the analyses was to develop prediction equations. Thus, it was planned to employ the variables which accounted for the most variation in infiltration from all three sets of comparisons in a final set of equations. However, only one of the soil chemical properties showed any promise, and individual soil profile descriptions were not made at enough points to utilize all the infiltration data. Thus, prediction equations were developed using only one chemical property and all of the variables in set 3. Path coefficient analyses were made to develop these equations.

Path Coefficient Analyses

In addition to the direct effects of independent variables on the dependent infiltration parameters, there are also indirect effects (interactions) which may be important. Path coefficients analysis was used to isolate these effects.

Li (1956) describes the concept of path coefficients as a special type of multivariate analysis that provides a method of dealing with a "closed" system of variables that are linearly related. He defined a closed system as one in which "each variable in the system is either a linear combination of some other variables in the system or is one of the basic factors, which may be correlated with or independent of other basic factors in the systems." In other words, the system is formally complete, including all the basic factors "causes" and the resultant variables "effects."

The method used to calculate path coefficients follows:

The path coefficient from the independent variable, X, to the dependent variable, Y, is defined as the portion of the standard deviation of Y that is due to the variation in X. The Direct Effect path coefficients are calculated as

$$b = P_{yx} = \frac{B\sigma_x}{\sigma_y} \qquad (12)$$

where $b = p_{yx}$ = the path coefficient for the direct path from X to Y.

B = the regression coefficient of Y on X.

σ_x = the standard deviation of X.

σ_y = the standard deviation of Y.

When the independent factors are uncorrelated, the path coefficient is simply the ordinary correlation coefficient between the two variables.

When the independent or causal factors are correlated, the following relations hold:

$$r_{yx} = P_{yx} + r_{xz}P_{yz} \tag{13}$$

$$r_{yz} = P_{yz} + r_{xz}P_{yz} \tag{14}$$

The first equation shows that the correlation between X and Y is the sum of the values of the two paths connecting them. The total correlation, r_{yx}, has been divided into the following two components: the component P_{yx} which measures the influence of the direct path from X to Y, and the second component $r_{xz}P_{yz}$ which measures the influence of the indirect path.

RESULTS AND DISCUSSION

Conductivity Parameters

A general quadratic equation was used in a stepwise regression analysis of hydraulic conductivity versus the soil physical properties measured in the study. Table 1 shows the coefficients of determination (R^2) obtained for each step in the regression program. The table also lists the regression coefficients with the respective variable for the last significant step in the analysis.

Regressions were run both including and excluding maximum water content since it was thought that this factor would integrate the effect of a number of the other variables. However, only slightly over one-half of the variation in hydraulic conductivity could be accounted for by either analysis. Beyond bulk density only an additional 15 percent of the variation was accounted for by all of the other variables.

Although the equations in Table 1 are perhaps not too reliable for prediction purposes, they illustrate the problem of interpreting multilinear regression analysis when correlation exists between the independent variables. Stepwise regression analysis causes the factor which accounts for most of the variation to enter the program as step one. Even though another factor may account for only slightly less

Table 1. Regression of hydraulic conductivity on soil physical properties.
Regression constant .002303.

	With Maximum Water Content Regression constant .002303				Without Maximum Water Content Regression constant .003701			
Step	Variable	R^2	Coefficient	F Ratio	Variable	R^2	Coefficient	F Ratio
1	X_1	0.42	-.0008400	33.04**	X_1	0.42	-.0037526	33.04**
2	X_3^2	0.44	-.0001026	17.51**	X_3^2	0.44	-.0001028	17.51**
3	X_8^2	0.45	-.0001136	12.03**	X_1^2	0.45	-.0001048	11.94**
4	X_2	0.46	.0000904	9.02**	X_2	0.46	.0000843	9.01**
5	X_2^2	0.52	-.0002484	9.42**	X_2^2	0.53	-.0002413	9.50**
6	X_5	0.53	.0035910	7.79**	X_4^2	0.54	.0036864	7.86**
7	X_5^2	0.54	.0164491	6.80**	X_4	0.55	.0144879	6.79**
8	X_4^2	0.55	-.0000232	5.99**	X_5	0.56	.0007024	5.91**
9	X_4	0.56	-.0005609	5.34**	X_5^2	0.56	.0000028	5.33**
10	X_3	0.56	.0000029	4.70**	X_3	0.56	.0000010	4.68**
11	X_6^2	0.56	.0000011	4.17**	X_6^2	0.56	-.0000012	4.16**
12	X_6	0.56	-.0000013	3.74**	X_6	0.56	.0000317	3.73**
13	X_7	0.56	.0000310	3.37**	X_7	0.56	-.0069519	3.35**

Table 1--Continued

	With Maximum Water Content Regression constant .002303				Without Maximum Water Content Regression constant .003701			
Step	Variable	R^2	Coefficient	F Ratio	Variable	R^2	Coefficient	F Ratio
14	X_7^2	0.57	-.006553	3.08**	X_7^2	0.56	-.0255921	3.07**
15	X_8	0.57	-.0288569	2.80**				
16	X_1^2	0.57	-.0000003	2.55*				

Legend

X_1 Bulk density

X_2 Sand

X_3 Silt

X_4 Clay

X_5 Org. m.

X_6 0.33 Bar

X_7 0.66 Bar

X_8 Water Content

variation it may be entered into the program in one of the later steps.

Bulk density accounted for most of the total variation accounted for in both regressions in this analysis. The correlation between bulk density and maximum water content was $r = 0.85$. Thus, the stepwise analysis caused bulk density to be entered first and maximum water content to be entered later in steps 3 and 15.

Causal factors, therefore, cannot be determined from the information derived from the stepwise multiple linear regression analysis where correlation exists between independent variables. Its main use in this study was to provide prediction equations. However, the total variation in hydraulic conductivity accounted for was too low for prediction purposes. This may have been due to the high variation encountered in measuring saturated conductivity. Although all possible care was taken with the measurements, entrapped air due to the small pore sizes in the clay loam soils was believed to be the major source of variation.

Infiltration Parameters

The "S" and "A" parameters of equation (9) and the infiltration capacity at $t = 1000$ seconds determined for the combined runs at all sampled points are given in Table 2. Coefficients of determination

Table 2. S and A parameters of equation (9) and infiltration capacity at t=1000 seconds

Location	"S" Parameter	"A" Parameter	R^2	Infiltration Capacity
3-86	3.56 E-02	1.32 E-03	0.98	.162 E-02
3-90	1.17 E-01	5.25 E-03	0.96	.620 E-02
6-106	1.08 E-01	6.62 E-04	0.87	.160 E-02
6-41	1.03 E-02	2.01 E-03	0.93	.210 E-02
6-82	7.35 E-03	2.65 E-04	0.96	.033 E-02
6-92	5.62 E-02	1.82 E-03	0.91	.229 E-02
6-75	9.15 E-02	2.97 E-03	0.92	.373 E-02
11-67	1.40 E-02	2.94 E-03	0.91	.306 E-02
11-134	1.33 E-01	3.58 E-03	0.90	.470 E-02
11-85	2.57 E-02	6.47 E-04	0.90	.086 E-02
11-43	2.73 E-02	2.55 E-03	0.88	.278 E-02
11-76	8.75 E-02	1.91 E-03	0.93	.264 E-02
11-61	2.43 E-02	1.20 E-03	0.99	.140 E-02
9-63	2.88 E-02	5.50 E-04	0.97	.079 E-02
9-61	4.62 E-02	2.39 E-03	0.97	.278 E-02
9-60	1.62 E-02	6.34 E-04	0.96	.077 E-02
9-52	9.14 E-03	1.23 E-04	0.85	.020 E-02
9-23	1.26 E-02	9.69 E-04	0.91	.107 E-02
9-16	1.56 E-01	1.82 E-03	0.93	.310 E-02
9-32	1.41 E-02	1.19 E-03	0.83	.131 E-02
9-81	7.13 E-02	1.31 E-03	0.87	.190 E-02
9-124	2.42 E-02	1.40 E-03	0.91	.160 E-02
9-104	4.07 E-02	1.03 E-03	0.99	.137 E-02
9-90	1.22 E-02	9.97 E-05	0.98	.020 E-02
9-46	9.76 E-02	1.46 E-03	0.97	.227 E-02
9-83	3.94 E-02	3.32 E-04	0.96	.066 E-02
9-110	5.10 E-03	5.35 E-04	0.92	.049 E-02
9-68	8.36 E-02	2.11 E-03	0.84	.281 E-02
9-91	1.40 E-02	1.81 E-04	0.83	.030 E-02
9-22	1.09 E-02	7.79 E-04	0.84	.087 E-02
9-117	1.11 E-02	3.88 E-05	0.96	.013 E-02
9-57	1.56 E-01	1.82 E-03	0.95	.310 E-02
12-113	1.10 E-02	5.82 E-04	0.90	.019 E-02
12-120	1.42 E-02	1.23 E-03	0.81	.023 E-02

and simple correlation coefficients are also presented. Those instances where the R^2 values fall below 0.98 are due to combining replicate runs that differed from each other. In no instances were R^2 values less than 0.98 for regressions made on the individual replications. The excellent agreement between theory and measurement data indicates the reliability of the diffusion approach for describing the infiltration phenomena.

According to the theory, infiltration into initially dry soils and at early times is governed by the sorptivity which, according to Phillips, is essentially a measure of the capacity of a soil to absorb or desorb liquid by capillarity. Since the field infiltration runs were made after the soils had been wetted by early summer rains, the sorptivity parameter determined does not make a large contribution to the regressions as indicated by the simple correlation coefficients. The extent to which the contribution to S is dependent upon initial water content is illustrated in figure 4. The initial water content of infiltration run 6-92-1 was 22.8 percent and that of run 6-41-2, 16.2 percent.

The two figures also illustrate the small error introduced by forcing the regression through the origin. Field points coincide nicely with the regression line throughout the range of data. In addition, tests made on three runs picked at random whose regressions were not

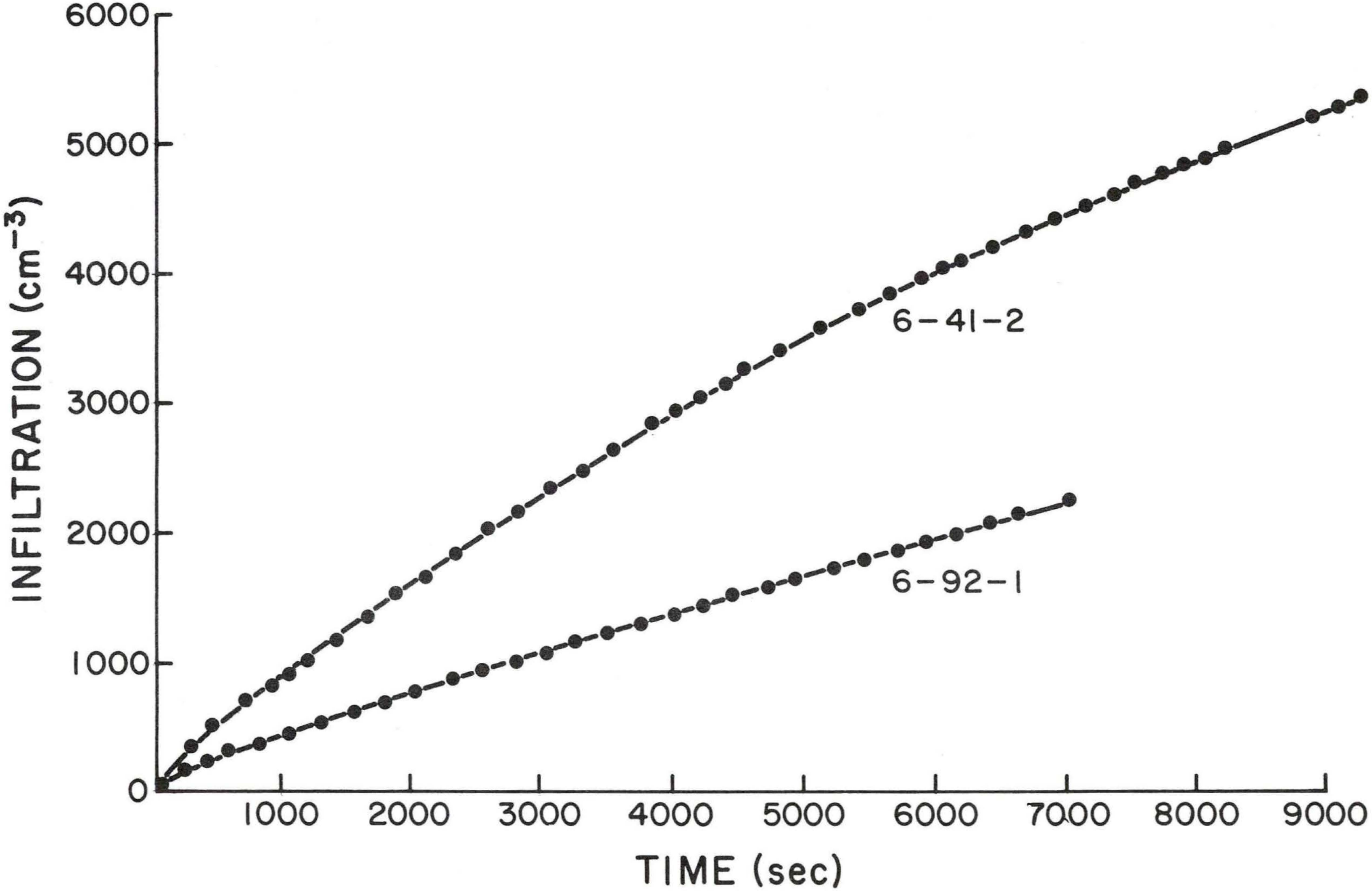

Figure 4. Infiltration versus time for two antecedent moisture conditions.

forced through the origin showed no significant difference between values of computed intercepts and zero.

It is clear that as $t \rightarrow \infty$, equation (9) fails because for very long times infiltration capacity approaches the saturated conductivity K. That is,

$$i = K \ .$$

Equations (9) and (6) would agree if A=K, but according to equation (8) this cannot be true. A semi-empirical method of reconciling equations (9) and (6) has been developed (Philip, 1957a). Nevertheless, a proportional relationship between A and K exists as demonstrated in the simplified development presented in the literature review. The relationship found in this study is shown in figure 5. Perhaps some of the variations could have been reduced had sample cores been taken directly from inside the infiltrometer rings.

Infiltration vs Chemical Properties

The correlation between the infiltration parameters and soil chemical properties was poor. Less than 50 percent of the variation in any of these parameters was accounted for by regression as shown in Tables 3 through 5. The tables list the variables and their associated R^2 value in the order of their entry into the stepwise analysis. The regression coefficients are listed with the respective variable for the last significant step in the analysis.

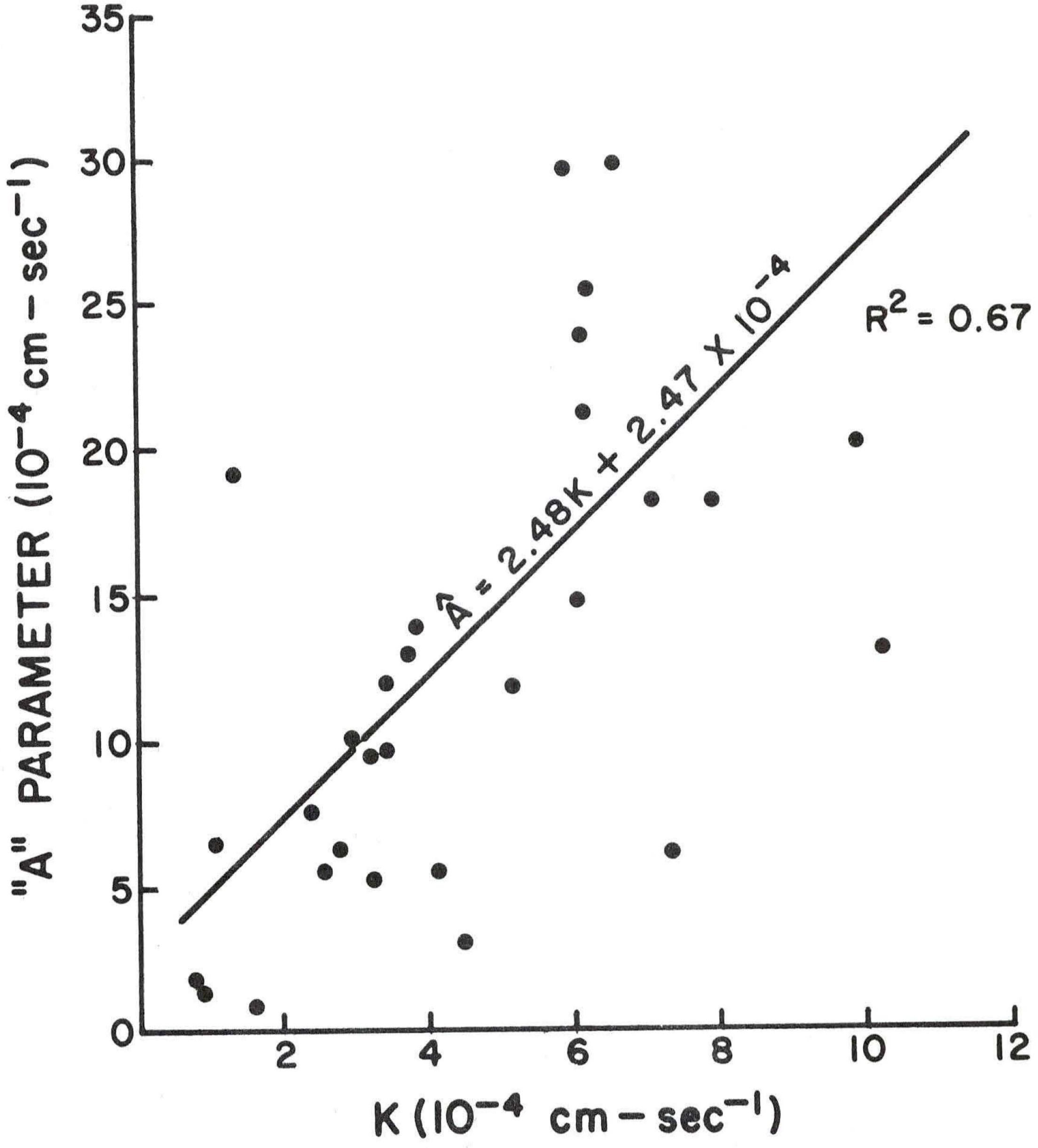

Figure 5. Relationship of "A" parameter to conductivity.

Table 3. Regression of Sorptivity on Soil Chemical Properties

Step	Variable	R^2	Correlation Coefficient	F Ratio
1	X_3^2	0.015	-0.030	.43 NS
2	X_5	-0.021	-0.054	.29 NS
3	X_5^2	0.068	-0.007	.64 NS
4	X_4^2	0.085	-0.020	.59 NS
5	X_1^2	0.087	0.041	.46 NS
6	X_1	0.157	0.029	.71 NS
7	X_4	0.183	0.007	.70 NS
8	X_3	0.200	-0.098	.66 NS
9	X_2	0.203	0.011	.56 NS
10	X_2^2	0.216	-0.030	.52 NS

Table 4. Regression of "A" parameter on soil chemical properties, regression constant --- .11749

Step	Variable	R^2	Correlation Coefficient	Regression Coefficient	F Ratio
1	X_1^2	0.190	0.43	-.038175	6.56*
2	X_1	0.322	0.42	-.000023	6.42**
3	X_5	0.373	-0.15	-.008786	5.15**
4	X_5^2	0.383	-0.11	.003187	3.88*
5	X_3	0.388	-0.22	.006472	3.04*
6	X_4	0.394	-0.14		2.49 NS
7	X_4^2	0.414	-0.12		2.22 NS
8	X_2^2	0.414	-0.11		1.86 NS
9	X_2	0.446	-0.15		1.79 NS
10	X_3^2	0.450	-0.15		1.56 NS

Table 5. Regression of infiltration capacity on soil chemical properties, regression constant -- 0.11564

Step	Variable*	R^2	Correlation Coefficient	Regression Coefficient	F Ratio
1	X_1^2	0.076	0.28	-.036990	2.32 NS
2	X_1	0.310	0.25	.000006	6.06 **
3	X_3	0.357	-0.22	-.000050	4.82 **
4	X_2	0.376	0.09	.000990	3.77 *
5	X_2^2	0.394	0.05	.002956	3.12 *
6	X_4	0.397	-0.05	-.00000008	2.52 NS
7	X_4	0.464	-0.03	-.000180	2.72 *
8	X_5^2	0.473	-0.03		2.36 NS
9	X_5	0.476	0.07		2.02 NS
10	X_3^2	0.476	-0.15		1.73 NS

*X_1 = pH

X_2 = Soluble salts

X_3 = NO_3

X_4 = PO_4

X_5 = ETDA

Overall correlation between soil chemical properties and infiltration parameters was extremely poor for sorptivity but somewhat better for the "A" parameter and infiltration capacity. Soil pH was the only variable that made worthwhile contributions to the regressions. When squared it was positively correlated and was entered first into the regressions for both the A parameter and infiltration capacity. The linear form of the variable was negatively correlated and entered second in both cases. This indicates there may be some optimum pH value below and above which infiltration drops off. Optimum values calculated from the regression equations in Tables 4 and 5, setting $\frac{\partial A}{\partial X_1} = 0$ and $\frac{\partial I}{\partial X_1} = 0$, were 6.25 for the A parameter and 6.11 for infiltration capacity.

It is conceivable that these values may be related to soil structure and therefore permeability, but unfortunately the low correlation obtained confutes definite statements. Similarly, little reliability can be placed on the relationship obtained with NO_3, the next highest correlated variable.

Infiltration vs Soil Profile Characteristics

The qualitative descriptive data on the soil profiles was coded for regression analysis as follows:

Structure

1. Subangular blocky
2. Blocky
3. Massive
4. Platy
5. Prismatic
6. Granular

Dry Consistency

1. Slightly hard
2. Hard
3. Very hard
4. Extremely hard

Moist Consistency

1. Friable
2. Very friable
3. Firm
4. Very firm

Wet Consistency

1. Sticky-Plastic
2. Slightly sticky-plastic
3. Slightly sticky-very plastic
4. Very sticky-very plastic

Considerable variation in the regression was accounted for in the final step of the analysis (Table 6). Structure of the B horizon, the highes correlated variable, was entered in step one of the analysis. However, structure of the A horizon was not highly correlated and was entered fourth. Since structure was ranked from what was believed to be most to least conducive to infiltration the relationship appears to be contrary to what might be expected. However,

TABLE 6. Regression of infiltration on soil profile characteristics regression constant -- .0.001135.

Step	Variable*	R^2	Correlation Coefficient	Regression Coefficient	F Ratio
1	X_3	.16	.3953	-.000820	3.89 NS
2	X_4	.31	.2698	-.001664	4.59*
3	X_8^2	.41	-.0832	.001892	4.37*
4	X_2^2	.49	.1935	.001648	4.36*
5	X_2	.64	.1126	-.005101	6.11**
6	X_1	.68	-.1981	.000502	5.72**
7	X_9	.70	-.0609	.000127	4.92**
8	X_5^2	.71	-.1250	.001005	4.30**
9	X_7	.72	-.0274	.000283	3.65*
10	X_7^2	.76	-.0307	.001195	3.77*
11	X_5	.78	-.1471	-.000013	3.58*
12	X_8	.80	-.1463	-.000006	3.39*
13	X_9^2	.81	.0105	-.000329	3.06*
14	X_1^2	.83	-.2108		2.72 NS
15	X_6	.83	-.2890		2.23 NS
16	X_6^2	.83	-.2980		1.80 NS

*X_1 = Depth to A Horizon
X_2 = Structure A
X_3 = Structure B
X_4 = Consistency Dry
X_5 = Consistency Moist
X_6 = Consistency Wet
X_7 = Gravel Percent
X_8 = Cobbel Percent
X_9 = Litter

these may be due to the generally higher infiltration capacity found on the Springerville soils which is discussed later. The Springerville soils have a granular A horizon underlain by a massive C horizon. Some of the other soils studied also have a granular A horizon but are underlain by structured B horizon. Thus on a three dimensional surface where infiltration is the dependent variable and structure of the A and B layers are independent variables, there should be some minimum tangent plane above which infiltration increases. This is borne out by the positive linear and negative quadratic coefficients associated with the A horizon structures.

Infiltration vs Soil Physical and Chemical Properties

Path Coefficient Analysis

Path coefficient analysis was made for the purpose of selecting meaningful interactions between variables for use in the development of prediction equations. Only infiltration capacity was considered in the analysis for simplicity and because it embodies both the sorptivity and "A" parameter. The data used in the analysis are given in Tables 7 and 8. These data were obtained from regression analysis using untransformed variables in a simple linear equation of the general form

$$Y = b_o + b_1X_1 + b_2X_2 + \text{-------} b_nX_n \quad . \tag{16}$$

Table 7. Data from regression analysis of soil physical properties (including conductivity) on infiltration capacity used in the path coefficient analysis

Step	Variable	R^2	Correlation Coefficient	Standard Deviation	Regression Coefficient
1	K	0.65	0.804	0.0003	2.683386
2	Water %	0.66	-0.213	5.229	-0.000030
3	0.66 b.	0.69	0.448	3.114	0.000113
4	pH	0.70	0.267	0.488	-0.000297
5	BD	0.70	0.273	0.139	0.001538
6	OM	0.71	-0.017	1.081	0.000135
7	0.33 b.	0.71	0.318	3.171	-0.000066
8	Sand	0.72	-0.342	5.170	-0.000197
9	Silt	0.72	-0.215	7.075	-0.000159
10	Clay	0.75	-0.330	8.667	-0.000178

Regression constant, 0.01676
Standard dev. infil. cap., 0.0014

Table 8. Data from regression analysis of soil physical properties (not including conductivity) on infiltration capacity used in the path coefficient analysis

Step	Variable	R^2	Correlation Coefficient	Standard Deviation	Regression Coefficient
1	0.66	0.20	0.448	3.114	0.000294
2	Water %	0.28	-0.213	5.229	-0.000025
3	Sand	0.30	-0.342	5.170	-0.000281
4	pH	0.31	0.267	0.488	0.000329
5	Clay	0.31	0.330	8.667	-0.000253
6	Silt	0.36	-0.215	7.075	-0.000202
7	BD	0.37	0.273	0.139	0.001547
8	0.33	0.38	0.318	3.171	-0.000086
9	OM	0.38	-0.017		

Regression constant, 0.016297
Standard dev. infil. cap., 0.0014

Since conductivity may integrate the effects of several of the other variables, regressions were run using equation (16) both with and without hydraulic conductivity as an independent variable. Over 75 percent of the variation in infiltration capacity was accounted for when hydraulic conductivity was entered. Only 38 percent could be accounted for when it was omitted. Among the other variables, initial water content and suction at 0.66 bars made the greatest contributions. Organic matter was very poorly correlated with infiltration capacity.

Correlation measures only mutual relationship without concern to causation, whereas the path coefficient analysis specifies the causes and measures their relative importance. Comparison of these two methods leads to some interesting speculations on the physical relationships between variables. Comparisons may be made among the correlation coefficients given in Tables 7 and 8 which are further partitioned by path coefficient analysis into their direct and indirect components in Tables 9 and 10. These tables are read from left to right. For example, the magnitude of the indirect effect of clay operating on infiltration through 0.66 bars is 0.306.

Initial water content is negatively correlated with infiltration as might be expected. The direct effects are also negative indicating an inverse relationship throughout the range of measurements. The

Table 9. Direct and indirect effects from path coefficient analysis (not including conductivity).

	Direct Effects	Sand	Silt	Clay	0.33b.	0.66b.	BD	OM	Water %	pH
Sand	-1.027		-.090	1.028	.062	-.166	-.090	.013	-.037	-.035
Silt	-1.004	-.092		1.194	.066	-.251	-.081	.007	-.013	-.043
Clay	-1.536	.687	.780		-.088	.306	.116	-.014	.027	.052
0.33b.	-.202	.314	.330	-.674		.513	.034	.011	-.029	.022
0.66b.	.642	.266	.393	-.733	-.161		.029	.011	-.016	.020
BD	.163	.566	.500	-1.087	-.041	.114		-.018	.025	.052
OM	.032	-.421	.233	.652	-.067	.216	-.093		-.017	-.049
Water %	-.101	-.380	-.130	.414	-.059	.105	-.040	.017		-.039
pH	.120	.299	.357	-.667	-.037	.104	.071	-.013	.032	

Table 10. Direct and indirect effects from path coefficient analysis (including conductivity).

	Direct Effects	Sand	Silt	Clay	0.33b.	0.66b.	BD	OM	Water %	pH	K
Sand	-.728		-.072	.737	.046	.065	-.084	.043	-.042	.030	-.206
Silt	-.804	-.065		.857	.049	-.098	-.076	.024	-.015	.037	-.122
Clay	-1.102	.487	.625		-.066	.120	.108	-.044	.030	-.045	.213
0.33b.	-.150	.222	.264	-.483		.201	.031	.035	-.033	-.019	.248
0.66b.	.251	.189	.315	-.526	-.119		.027	.035	-.018	-.017	.311
BD	.153	.401	.400	-.780	-.031	.045		-.060	.027	-.045	.159
OM	.104	-.298	-.187	.468	-.050	.085	-.087		-.060	.042	-.033
Water %	-.112	-.269	-.104	.297	-.044	.041	-.037	.056		.033	.073
pH	-.103	.212	.286	-.478	-.028	.041	.066	-.043	.036		.277
K	.730	.205	.134	-.322	-.051	.107	.033	-.005	.011	-.039	

indirect effects operating through the other variables have little physical significance.

Soil pH, on the other hand, is positively correlated with infiltration but exerts a negative direct effect when analyzed with conductivity and a negative indirect effect operating through the 0.33 bar suction variable. This indicates that high pH may operate to reduce infiltration to a certain extent.

The effect of clay is somewhat similar. It is positively correlated with infiltration when considered both with and without conductivity, but exerts a negative influence in its direct effect. This indicates infiltration is enhanced by a certain amount of clay but may drop off as clay content increases.

The indirect effects of clay are interesting when operating through 0.33 and 0.66 bars. There is a negative effect through 0.33 bars and a positive effect through 0.66 bars which may be due to pore size distribution characteristics. Additional work on water release by these soils would be necessary to clarify this relationship.

The 0.66 bar variable is positively correlated with infiltration and exerts a positive direct effect. Interestingly, it shows a negative indirect influence on initial water content. This effect may be tied in with the complex interrelationships between percentages of sand, silt and clay. Sand and silt are negatively correlated with

infiltration and operate in a negative fashion both directly on infiltration and indirectly through the other variables. Unfortunately, the range in texture for the different soils was very small, and all were classed as clay loams. Thus, the relationships shown are those for a very narrow band of the textural spectrum. The negative influence of the coarser separates and the generally positive influence of clay might be tied in with soil cracking. Although the soils were moist when infiltration runs were made, microcracks sometimes persist for extended periods and may benefit infiltration.

The effects of bulk density may also be associated with clay content and cracking. Correlation coefficients and the meaningful direct and indirect effects were positive. Bulk density was determined on air dried clods. The clods with the higher clay content, chiefly montmorillonite, tended to shrink to a smaller volume and sometimes exhibited a greater density.

Development of Prediction Equations

In the path coefficient analysis all possible indirect paths were considered, a great number of which had little or no physical significance. Among those that were physically realistic only a few exerted a significant effect on infiltration. Paths believed to have some physical significance in the analysis which did not include

hydraulic conductivity are given in figure 6. A figure for the analysis which included conductivity is not shown because of the large number of possible combinations.

In the analysis which did not include conductivity the interrelationships that made worthwhile contributions were:

Silt through 0.66 bars
Clay through 0.66 bars

In the analysis which included conductivity the interrelationships that contributed most were:

Sand through conductivity
Clay through conductivity
0.33 bars through conductivity
pH through conductivity

These interactions were used in the development of the prediction equations. Because of the high variability in the data and because there are no theoretical functions that describe the relationships studied, a quadratic equation of the general form

$$Y = b_o + b_1X_1 + b_1X_1^2 + \ldots . b_{(2n-1)}X_n + b_{2n}X_n^2 \qquad (17)$$

was used as the empirical model for the prediction equation. The interaction variables were not squared. Results of the stepwise regression analysis are given in Tables 11 through 16. These tables list a series of equations, one for each additional variable as it was entered into a program and the associated coefficient of determination. It should be

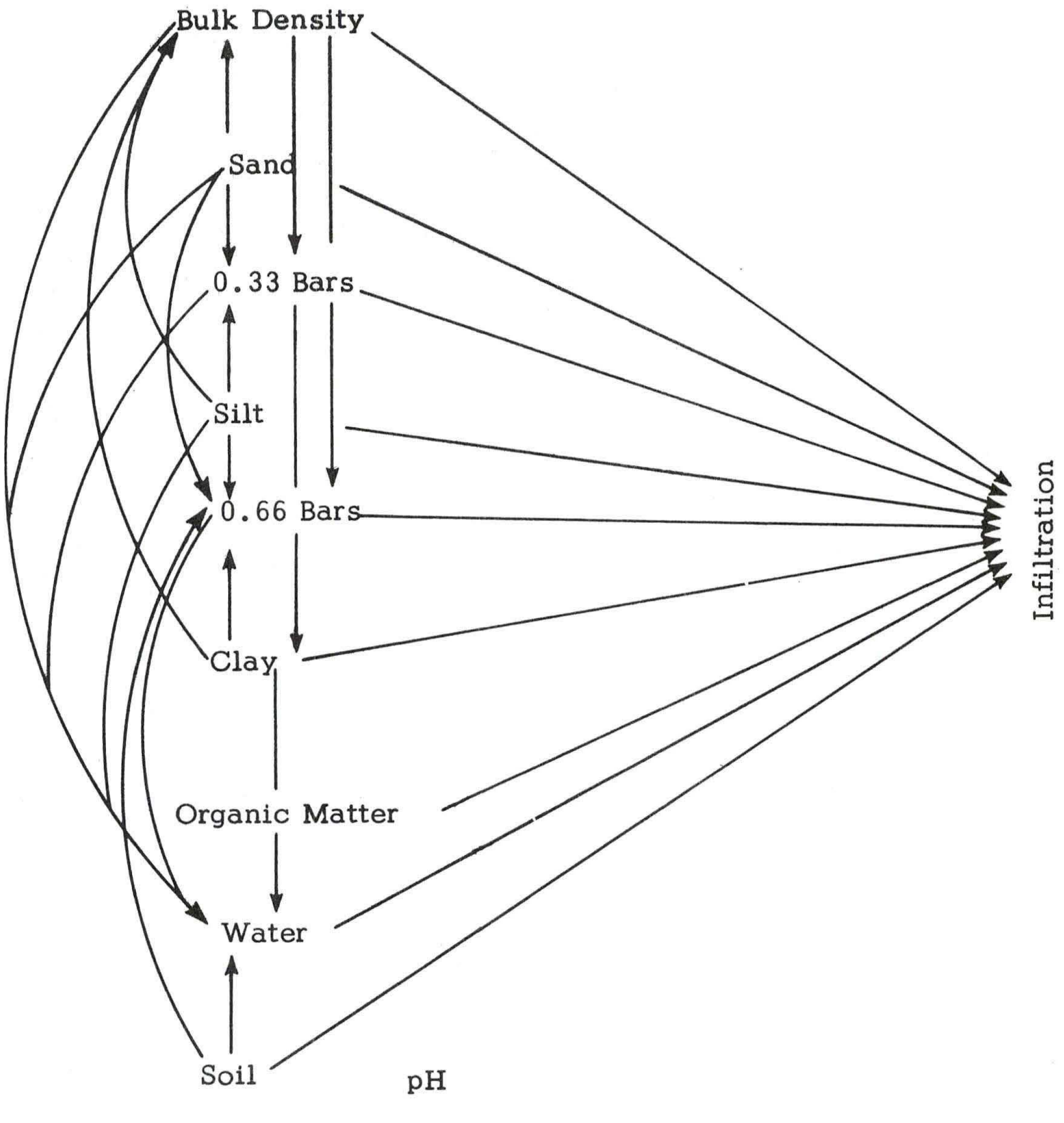

Figure 6. Diagram showing possible interrelationships of the variables used in the path coefficient analyses to determine the direct and indirect effects of the causal factors on infiltration.

Table 11. Regression equations of soil physical properties and the "A" parameter

Intercept Constant	X_{21}	X_1	X_{11}	X_{22}	X_{20}	X_{10}	X_{13}	X_2	X_{23}	X_{14}	X_{17}	X_{24}	X_4	X_9	X_3	X_{12}	X_{19}	X_8	X_5	X_{15}	X_{18}	X_7	X_6	X_{16}	R^2	F Ratio
.0101	5.741																								.25	10.25 **
.0479	7.076	-.0031																							.36	8.23 **
.0979	6.935	-.0103	.00024																						.39	6.13 **
.1656	10.902	-.0176	.00038	-1.226																					.46	5.79 **
.1826	11.884	-.0176	.00036	-3.650	63363																				.54.	6.13 **
.2271	40.205	-.0144	.00004	2.073	215851	- 745.9																			.69	9.15 **
.3456	46.508	-.0229	.00020	5.180	215194	- 035.3	-.00003																		.70	8.09 **
.6699	45.528	-.0310	.00033	4.758	210301	- 904.1	-.00008	-.003																	.72	7.49 **
.6925	44.554	-.0320	.00036	3.997	200595	- 920.7	-.00008	-.004	2.285																.73	6.52 **
.7847	38.561	-.0320	.00038	.329	129269	-1031.4	-.00007	-.004	16.410	-.0001															.78	7.24 **
.8350	33.566	-.0318	.00041	-1.661	86422	-1041.6	-.00005	-.004	23.278	-.0002	.002														.80	7.16 **
.8889	31.098	-.0343	.00049	-1.405	78161	- 930.8	-.00006	-.005	25.555	-.0002	.002	-22.902													.81	6.65 **
.5933	30.939	-.0358	.00053	- .890	77814	- 934.3	-.00007	-.005	25.522	-.0006	.002	-25.247	.022												.82	6.16 **
.5111	30.034	-.0344	.00050	-1.273	83225	- 856.1	-.00006	-.005	26.626	-.0006	.002	-39.877	.022	.013											.82	5.58 **
.2196	33.387	-.0350	.00052	- .755	95316	- 939.7	-.00012	-.003	26.646	-.0007	.002	-38.742	.027	.017	.006										.83	5.10 **
-.3466	39.069	-.0150	.00033	-1.043	148716	-1130.3	-.00024	-.038	24.403	-.0009	.002	-16.475	.042	-.003	.029	.0005									.86	5.68 **
-1.8395	38.521	-.0178	.00043	.325	149576	-1235.7	-.00026	-.042	28.731	-.0011	.002	-25.411	.048	.492	.031	.0005	-.040								.87	5.31 **
-2.6996	40.867	.0113	.00037	1.007	184077	-1306.1	-.00026	-.051	28.020	-.0011	.002	-25.361	.053	.712	.036	.0007	-.059	-.001							.87	4.86 **
-2.5896	41.994	-.0111	.00036	1.267	189395	-1329.1	-.00028	-.052	26.113	-.0011	.002	-18.322	.055	.656	.037	.0007	-.054	-.001	.001						.87	4.31 **
-2.1390	37.968	-.0031	.00022	-1.797	170641	-1211.5	-.00027	-.049	28.800	-.0008	.002	-21.633	.033	.261	.040	.0007	-.022	-.002	.062	-.001					.90	4.96 **
1.5820	35.568	.0098	-.00028	-5.642	169506	- 871.4	-.00009	-.020	20.765	-.0003	.0002	-13.561	.007	-.824	.021	.0003	.067	-.027	.067	-.001	.0005				.91	4.62 **
1.0961	34.250	.0065	-.00021	-6.649	151412	- 930.6	-.00011	-.018	27.055	-.0003	.0032	-20.286	.008	-.673	.022	.0003	.055	-.024	.070	-.001	.0004	-.018			.91	4.07 *
1.4297	35.142	.0034	-.00018	-7.015	145326	- 935.5	-.00011	-.014	29.637	-.0002	.0004	-29.273	.0003	-.732	.020	.0002	.060	-.024	.074	-.001	.0004	-.027	- .032		.91	3.51 *
.3489	32.439	.0191	-.00041	-6.551	185735	-1099.8	-.00025	-.027	27.428	-.0009	.0017	1.385	.0367	-.149	.037	.0004	.012	-.030	.060	-.001	.0005	.001	-2.033	.722	.93	4.09 *

X_1 Sand

X_2 Silt

X_3 Clay

X_4 .33 bars

X_5 .66 bars

X_6 B.D.

X_7 O.M.

X_8 Water %

X_9 pH

X10 conductivity

Table 12. Regression equations of soil physical properties and the sorptivity parameters

Intercept Constant	X_{23}	X_8	X_{24}	X_{18}	X_{10}	X_2	X_4	X_{14}	X_{22}	X_1	X_{16}	X_{19}	X_9	X_{17}	X_6	X_{21}	X_{20}	X_{15}	X_5	X_7	X_{12}	X_{13}	X_3	X_{11}	R^2	F Ratio
.0003	.077																								.69	65.96**
.0015	.075	-.00004																							.72	37.64**
.0020	.217	-.00006	-.667																						.76	29.36**
.0063	.218	-.00039	-.659	.00001																					.79	25.20**
.0066	.189	-.00042	-.938	.00001	2.924																				.81	21.61**
.0082	.178	-.00047	-.987	.00001	3.597	-.00002																			.82	18.76**
.0133	.314	-.00059	-1.330	.00001	1.894	-.00003	-.001																		.84	17.49**
.0204	.287	-.00057	-1.308	.00001	2.555	-.00003	-.001	.00001																	.84	15.56**
.0222	.329	-.00056	-1.139	.00001	1.680	-.00004	-.001	.00001	-.037																.85	13.91**
.0257	.412	-.00057	-1.074	.00001	.720	-.00007	-.001	.00001	-.087	-.0001															.87	14.23**
.0307	.430	-.00056	-1.151	.00001	.806	-.00008	-.001	.00001	-.089	-.0001	-.001														.88	13.81**
.0324	.486	-.00054	-1.725	.00001	2.863	-.00008	-.001	.00001	-.091	-.0001	-.001	.00004													.90	13.51**
.0496	.454	-.00054	-1.708	.00001	4.217	-.00009	-.001	.00001	-.107	-.0001	-.001	.0015	-.005												.90	12.21**
.0756	.362	-.00060	-1.661	.00001	7.016	-.00010	-.001	.00002	-.121	-.0001	-.001	.0011	-.013	-.00003											.91	11.60**
.0759	.317	-.00054	-1.675	.00001	8.504	-.00011	-.001	.00002	-.126	-.0001	-.005	.0014	-.016	-.00004	.012										.91	10.70**
.0940	.276	-.00053	-1.432	.00001	4.875	-.00009	-.001	.00002	-.093	-.0001	-.007	.0019	-.023	-.00006	.018	.167									.92	10.21**
.0911	.105	-.00056	-1.616	.00001	2.148	-.00008	-.001	.00003	-.009	-.0002	-.009	.0019	-.023	-.00008	.023	.446	1944.7								.93	10.54**
.0943	.054	-.00060	-1.427	.00001	2.124	-.00007	-.001	.00003	-.008	-.0002	-.010	.0021	-.025	-.00009	.026	.458	1936.7	.000001							.93	9.69**
.0913	.052	-.00061	-1.408	.00001	1.636	-.00007	-.001	.00002	-.0004	-.0002	-.010	.0019	-.023	-.00010	.025	.467	2034.1	.00001	-.0003						.93	8.64**
.0941	-.018	-.00064	-1.311	.00001	2.400	-.00006	-.001	.00002	.0142	-.0002	-.009	.0020	-.024	-.00014	.023	.460	2101.3	.00001	-.0004	.0003					.93	7.63**
.0895	-.110	-.00061	-1.116	.00001	2.318	-.00021	-.001	.00002	.0432	-.0002	-.009	.0018	-.022	-.00018	.023	.464	2368.5	.00001	-.0006	.0005	.000002				.93	6.81**
.0850	-.121	-.00060	-1.170	.00001	2.976	-.00029	-.001	.00002	.0448	-.0001	-.011	.0017	-.021	-.00019	.029	.457	2442.8	.00001	-.0006	.0006	.000003	.000001			.94	5.96**
.0138	-.096	-.00077	-1.592	.00001	8.777	.00035	-.002	.00003	-.0019	-.0004	-.015	.0029	-.035	-.00017	.040	.383	1320.0	.00001	-.0004	.0003	.000006	.000004	-.0005		.94	5.53**
.2441	-.476	-.00154	-.951	.00002	18.589	.00099	-.002	.00005	1.0169	.0003	-.013	.0055	-.068	-.00030	.034	.336	2153.9	.00001	-.0003	.0007	-.00001	.000009	-.0009	-.00001	.95	5.78*

X_1 Sand — X_5 .66 bars — X_9 pH

X_2 Silt — X_6 B. D. — X_{10} conductivity

X_3 Clay — X_7 O. M.

X_4 .33 bars — X_8 Water %

Table 13. Regression equations of soil physical properties and the infiltration capacity

Intercept Constant	X_{19}	X_{12}	X_2	X_8	X_{18}	X_9	X_{20}	X_{21}	X_{24}	X_{22}	X_{11}	X_{13}	X_3	X_{15}	X_5	X_{14}	X_{17}	X_{23}	X_7	X_4	X_{16}	X_6	X_{10}	X_1	R^2	F Ratio
- .0091	.0003																								.11	3.83 NS
- .0234	.0004	.000004																							.28	5.65**
.0540	.0003	.00004	-.003																						.36	5.26**
.0550	.0004	.00004	-.003	.0002																					.40	4.44**
.0389	.0004	.00006	-.005	.004	-.0001																				.54	6.05**
.1878	.0039	.00006	-.005	.004	-.0001	-.045																			.57	5.49**
.3645	.0094	.00005	-.004	.004	-.0001	-.110	3627.5																		.63	5.77**
.4235	.0110	.00005	-.004	.004	-.0001	-.130	4761.0	.155																	.63	4.96**
.3986	.0102	.00005	-.004	.003	-.0001	-.120	2339.8	.537	- 2.150																.66	4.65**
.2014	.0054	.00005	-.004	.003	-.0001	-.058	8736.4	1.292	- 9.390	.816															.72	5.33**
.3077	.0089	.00004	-.003	.003	-.00004	-.100	11212.2	1.947	-10.299	.666	-.00001														.74	5.21**
.3865	.0113	.00002	-.002	.003	-.00004	-.127	11315.6	2.057	-10.409	.607	-.00003	-.00001													.77	5.45**
.2816	.0093	.00006	-.003	.004	-.00006	-.104	11177.6	2.003	-10.143	.607	-.00001	-.00002	.002												.80	5.52**
.2470	.0084	.00007	-.006	.004	-.00007	-.093	11497.8	1.922	- 9.973	.583	-.000003	-.00003	.002	.000004											.81	5.09**
.2701	.0064	.00007	-.006	.004	-.00007	-.067	13318.3	2.073	-10.706	.693	-.000004	-.00002	.002	.00012	-.006										.84	5.52**
.3371	.0065	.00005	-.004	.003	-.00004	-.069	11483.7	1.897	-10.018	.648	-.00002	-.00001	.001	.00018	-.009	-.00001									.86	5.71**
.5066	.0107	.00004	-.003	.002	-.00002	-.120	9447.7	1.946	- 9.004	.494	-.00003	-.00001	.0004	.00018	-.009	-.00001	-.0002								.87	5.52**
.7254	.0159	.00002	-.002	.001	-.00001	-.185	15829.0	3.077	- 5.652	.781	-.00005	-.00001	-.0002	.00021	-.010	.00001	-.0005	-1.893							.88	5.61**
.7468	.0162	.00003	-.003	.001	-.00001	-.189	19172.6	3.496	- 4.374	1.141	-.00004	-.00001	-.0001	.00023	-.011	-.00001	.0012	-2.982	.004						.89	5.26**
.8043	.0173	.00002	-.002	.001	-.000001	-.203	18504.7	3.528	- 4.201	1.081	-.00005	-.00001	-.0004	.00022	-.011	.00003	-.0011	-2.937	.004	-.001					.89	4.63**
.8727	.0188	.00002	-.002	.001	.000003	-.221	18839.9	3.742	- 5.118	1.009	-.00005	-.000004	-.0006	.00021	-.010	.00005	-.0010	-2.733	.002	-.002	-.002				.90	4.08*
.8813	.0230	.00002	-.002	.001	-.00001	-.273	20522.9	4.598	- 5.893	1.096	-.00005	.00001	-.0013	.00018	-.008	.00011	-.0009	-3.102	.001	-.005	-.090	.243			.92	4.99**
1.2546	.0319	-.00002	.001	-.0004	.00002	-.381	15945.7	3.833	- 7.321	.685	-.00007	.00003	-.0037	.00017	-.008	.00017	-.0011	-3.664	.001	-.009	-.102	.283	53.756		.93	4.65*
1.1654	.0295	.00002	.001	.0005	.00001	-.351	13557.8	3.893	- 8.717	.792	-.00005	.00002	-.0036	.00016	-.007	.00017	-.0009	-3.060	-.001	-.009	-.110	.302	44.028	.001	.93	3.98*

X_1 Sand

X_2 Silt

X_3 Clay

X_4 .33 bars

X_5 .66 bars

X_6 B.D.

X_7 O.M

X_8 Water %

X_9 pH

X_{10} conductivity

Table 14. Regression equations of soil physical properties and "A" parameter

Intercept Constant																						
- .0623	.075																				.05	1.62 NS
- .1664	.128	.012																			.10	1.70 NS
- .3263	.188	.072	-.010																		.25	3.05 *
- .2577	.154	.100	-.014	-.003																	.32	3.19 *
- .1083	.107	.107	-.015	-.015	.0003																.38	3.15 *
- .0859	.147	.120	-.016	-.018	.0004	-.0001															.44	3.27 *
- .8282	.171	.117	-.015	-.018	.0004	-.001	.048														.48	3.23 *
-1.1381	.206	.108	-.014	-.017	.0004	-.001	.060	.0001													.52	3.10 *
-1.0700	.199	.104	-.014	-.015	.0003	-.001	.058	.0001	-.0022												.53	2.76 *
- .0782	.201	.094	-.014	-.033	.0006	-.001	.050	.0004	-.016	-.0004											.63	3.57 **
.5340	--.506	.101	-.015	-.033	.0006	-.001	.045	.0004	-.016	-.0004	.242										.64	3.25 *
.7264	--.547	.101	-.015	-.032	.0006	-.001	.044	.0006	-.020	-.0004	.257	-.008									.64	2.85 *
1.6079	--.722	.102	-.016	-.034	.0006	-.001	.059	.0009	-.028	-.0004	.324	-.064	.001								.65	2.63 *
2.4101	--.601	.112	-.017	-.027	.0006	-.001	.068	.0014	-.058	-.0002	.281	-.114	.001	.0002							.67	2.49 *
2.8235	-1,075	.011	-.017	-.026	.0006	-.001	.080	.0015	-.069	.0002	.445	-.125	.001	.0003	-.0001						.68	2.73 NS
2.9234	-1.118	.114	-.017	-.024	.0006	-.001	.080	.0016	-.069	.0002	.461	-.130	.001	.0003	-.0001	-.001					.68	1.98 NS
3.2282	-1.382	.117	-.018	-.021	.0005	-.002	.081	.0017	-.066	.0002	.554	-.138	.001	.0003	-.0001	-.010	.0002				.68	1.79 NS
3.1702	-1.186	.117	-.018	-.022	.0005	-.001	.080	.0017	-.069	.0002	.485	-.137	.001	.0003	-.0001	-.010	.0002	-.005			.69	1.58 NS
4.1435	-1.221	.122	-.020	-.011	.0002	-.001	.065	.0013	-.049	-.0001	.498	-.092	.001	.0002	.0003	-.023	.0004	-.552	.044		.72	1.60 NS
4.4421	-1.315	.121	-.019	-.011	.0002	-.001	.066	.0013	-.048	-.00003	.531	-.100	.001	.0001	-.0003	-.025	.0005	-.553	.044	-.044	.72	1.40 NS

X_1 Sand X_5 .66 bars X_9 pH

X_2 Silt X_6 B.D.

X_3 Clay X_7 O.M.

X_4 .33 bars X_8 Water %

Table 15. Regression equations of soil physical properties and the sorptivity parameter

Inter-cept Con-stant	X_{14}	X_8	X_{18}	X_9	X_{17}	X_{16}	X_7	X_{10}	X_2	X_{12}	X_1	X_4	X_6	X_{20}	X_3	X_{19}	X_5	X_{13}	X_{15}	X_{11}	R^2	F Ratio
-.0008	.000003																				.23	8.85 **
.0010	.000004	-.0001																			.34	7.34 **
-.0002	.000003	-.0001	.00003																		.35	5.14 **
.0486	.000003	-.00004	.00128	-.020																	.45	5.45 **
.0567	.000003	-.00031	.00140	-.020	.00001																.47	4.55 **
.0653	.000004	-.00054	.00151	-.020	.00001	-.0001															.51	4.34 **
.0802	.000004	-.00073	.00190	-.024	.00001	-.0003	.002														.66	6.52 **
.0727	.000004	-.00065	.00175	-.022	.00001	-.0004	.002	-.000001													.68	6.16 **
.0782	.000003	-.00068	.00184	-.023	.00001	-.0004	.002	-.000002	-.00002												.69	5.56 **
.0829	.000003	-.00062	.00189	-.023	.00001	-.0003	.002	-.000003	-.00001	-.000001											.71	5.10 **
.0769	.000004	-.00045	.00162	-.020	.00001	-.0003	.002	.000002	-.00013	-.000001	-.0002										.72	4.59 **
.0798	.000004	-.00052	.00166	-.020	.00001	-.0003	.002	.000006	-.00013	-.000002	-.0002	-.0001									.72	4.09 **
.0786	.000004	-.00053	.00168	-.021	.00001	-.0003	.002	-.0000001	-.0001	-.000002	-.0002	-.0001	.001								.72	3.65 **
.0749	.000002	-.00050	.00161	-.020	.00001	-.0003	.002	-.000003	-.0001	-.000003	-.0002	-.0001	.001	.000003							.73	3.24 *
.0793	.000001	-.00052	.00163	-.020	.00001	-.0003	.002	-.000001	-.0001	-.000003	-.0002	-.0001	.001	.00001	-.0001						.73	2.87 *
.0820	.000007	-.00053	.00163	-.020	.00001	-.0003	.002	-.000001	-.0002	-.000003	-.0001	-.0001	.001	.00001	-.0002	.000004					.73	2.58 *
.1210	.000012	-.00062	.00146	-.020	.00001	-.0003	.002	-.000001	-.0007	-.000001	-.0002	-.0001	.001	.00002	-.0004	.000023	-.002				.75	2.44 *
.1214	.000018	-.00006	.00137	-.020	.00001	-.0003	.002	-.000001	-.0008	-.000002	-.0002	.0005	.001	.00002	-.0005	.000027	-.003	-.00001			.75	2.21 NS
.1582	.000018	-.00076	.00134	-.020	.00001	-.0003	.002	-.000003	-.0010	-.00001	-.0002	.0010	-.034	.00003	-.0006	.000037	-.004	-.00002	.012		.77	2.08 NS
.1568	.000018	-.00074	.00133	-.020	.00001	-.0003	.002	-.000002	-.0011	-.0001	-.0001	.0010	-.033	.00003	-.0006	.000037	-.004	-.00001	.012	.000001	.77	1.81 NS

X_1 Sand
X_2 Silt
X_3 Clay
X_4 .33 bars
X_5 .66 bars
X_6 B. D.
X_7 O. M.
X_8 Water %
X_9 pH
X_{10} conductivity

Table 16. Regression equations of soil physical properties and the sorptivity parameter

Intercept Constant	X_{18}	X_{11}	X_2	X_8	X_{17}	X_9	X_4	X_{13}	X_{14}	X_{19}	X_{12}	X_3	X_6	X_{16}	X_5	X_{10}	X_1	X_{15}	X_7	X_{20}	R^2	F Ratio
-.0091	.0003																				.11	3.83 NS
-.0234	.0004	.000004																			.28	5.65 **
.0540	.0003	.00004	-.003																		.36	5.28 **
.0550	.0004	.00004	-.003	.0002																	.40	4.44 **
.0389	.0004	.00006	-.005	.004	-.0001																.54	6.05 **
.1878	.004	.00006	-.005	.004	-.0001	-.045															.57	5.49 **
.2210	.005	.00006	-.005	.004	-.0001	-.053	-.0002														.58	4.74 **
.2629	.004	.00006	-.005	.004	-.0001	-.045	-.005	.0001													.61	4.48 **
.2539	.004	.00006	-.005	.004	-.0001	-.042	-.004	.0001	.00001												.62	3.95 **
.1765	.004	.00005	-.003	.003	-.00004	-.042	-.002	.00002	.0001	-.0001											.71	5.21 **
.2009	.004	.00006	-.003	.003	-.00004	-.052	-.002	.00002	.0001	-.0001	-.000002										.73	5.04 **
.0945	.004	.00007	-.003	.004	-.00005	-.040	.0002	-.00002	.0001	-.0001	-.00002	.002									.78	5.64 **
.0758	.004	.00007	-.004	.004	-.00005	-.041	.001	-.00003	.0001	-.0001	-.00002	.002	.005								.79	5.12 **
.0229	.003	.00007	-.003	.004	-.00006	-.034	.002	-.00005	.0001	-.0001	-.00003	.002	.008	.0002							.80	4.78 **
-.0411	.003	.00007	-.002	.004	-.00006	-.037	.001	-.00004	.0001	-.0002	-.00003	.002	.007	.0002	.004						.80	4.27 **
-.0090	.004	.00005	-.001	.004	-.00005	-.043	.001	-.00003	.0001	-.0001	-.00002	.001	.007	.0002	.004	-.00001					.80	3.82 **
.0116	.005	.00006	-.001	.003	-.00004	-.058	.0004	-.00003	.0001	-.0002	-.00002	.002	.008	.0002	.005	-.00003	.001				.81	3.50 *
-.0090	.005	.00006	-.001	.003	-.00004	-.057	.0004	-.00002	.0001	-.0002	-.00002	.001	.034	.0002	.005	-.00003	.001	-.009			.81	3.08 *
-.0162	.005	.00006	-.001	.003	-.00005	-.056	.0004	-.00002	.0001	-.0002	-.00002	.002	.038	.0003	.005	-.00003	.001	-.010	-.001		.81	2.70 *
-.0084	.005	.00006	-.001	.003	-.00005	-.056	.0004	-.00003	.0001	-.0002	-.00002	.002	.033	.0003	.005	-.00003	.001	-.009	-.001	.00001	.81	2.35 NS

X_1 Sand — X_5 .66 bars — X_9 pH

X_2 Silt — X_6 B.D. — X_{10} conductivity

X_3 Clay — X_7 O.M.

X_4 .33 bars — X_8 Water %

noted that the stepwise multiple linear regression selects the factor accounting for the most variation first and then computes the deviations associated with this factor. Then the factor accounting for the next greatest amount of variation is computed and so on. If there happens to be a factor included which is closely correlated to the first factor, it will not enter the program until near the end of run. Consequently, there could be two factors which are closely correlated to infiltration, one will be ranked relatively high in regard to its effect on infiltration and the other ranked low in regard to its effect. The equation derived from the stepwise multiple linear regression program can be used for predicting infiltration under given conditions, but they must be interpreted with caution when the actual causal factors are the main items of interest.

SUMMARY

Results of the study may be summarized as follows:

1. Infiltration characteristics of the Beaver Creek soils could be described very precisely by parameters developed from diffusion theory.

2. The parameters characterizing infiltration were not highly correlated with the soil chemical properties measured in the study but were highly correlated with soil physical properties and with soil profile characteristics.

3. Prediction equations developed from path coefficient analyses and regression analyses appeared adequate for estimating the infiltration capacity of Beaver Creek soils.

4. Use of the equations for predicting other infiltration parameters is limited to the conditions of antecedent moisture which prevailed during the study.

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SECTION 7

SATURATED FLOW OF WATER THROUGH CLAY LOAM SUBSOIL MATERIAL

OF THE BROLLIAR AND SPRINGERVILLE SOIL SERIES

by

Robert Franklin Blecker

LIST OF ILLUSTRATIONS

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ABSTRACT

The water transmission characteristics of subsoil material from the Brolliar and Springerville soil series of northern Arizona were determined. The flow behavior of the soils was ascertained using a system that measured the hydraulic head difference across a soil sample when known flow rates through the soil sample were being produced. Current theories for describing non-Darcy behavior together with quantitative expressions were used to describe and offer possible explanations for the hydrologic behavior of the soil materials. Extremely low permeability rates were found for both soils at all porosities and hydraulic gradients. The flow-hydraulic gradient relationship was found to be non-linear. Non-linearity was more pronounced at very low gradients for both soils. The Springerville soil materials with higher clay and salt content exhibited the least departure from linearity. As porosity increased, flow behavior became more Darcy-like for both soils. The flow behavior of these two major soil series have important implications to management of the watersheds where these soils are found.

INTRODUCTION

The northern central part of Arizona, above the Mogollon Rim, supplies a vital source of water to the state from the relatively large amount of precipitation that falls in the area. The climate is semi-arid and continental with cold winters and warm summers at the higher elevations and mild weather year around in the lower areas. The annual precipitation is 18-27 inches of which 40-45% is snow. The topography of the area is characterized by gentle slopes which have permitted moderately deep weathering and soil profile development.

The major soils of the area are derived from basalt parent material. The Springerville and Brolliar soils are typical of the soils in the region. The soils of the Springerville series are characteristically vertisols developed from the weathering basalt and cinders. The Brolliar soil series is characterized by deep to moderately deep profiles weathered from porous basalts. Both series cover extensive areas above the Mogollon Rim. The clay fraction of these soils is almost entirely montmorillonite which causes pronounced shrinking and swelling. Upon wetting, the subsoils swell and become exceedingly tight and very slowly permeable. This condition greatly affects the hydrologic behavior of the watershed areas where these soils are found. It has been suggested that if the soils were not of a shrinking nature the flow characteristics of the streams in these areas would be altered considerably.

The controlling influence on the regional hydrology of basaltic subsoil material has been surmised only in general qualitative terms. Little or no quantitative data are available on the water transmission characteristics of these important soil materials.

Objectives

The study had two major objectives:

1. To determine the water transmission characteristics of subsoil material from two major soil series of northern Arizona.

2. To investigate quantitative expressions and present theories for describing the hydrologic behavior of these materials.

Scope

The study was made under controlled conditions in the laboratory on prepared subsoil material. The soil material was a heavy montmorillonic clay loam which had been collected from the Brolliar and Springerville soil series by methods described in A Study to Determine the Hydrologic and Physical Properties of Some Beaver Creek Soils (Watershed Management Dept. 1968). Flow characteristics of the soil materials were determined with a system that measured the hydraulic head difference across a soil sample when known flow rates through the soil sample were being produced. A range of bulk densities, which are normally found under field conditions, was used in the study to determine the effect porosity would have on the flow characteristics of the soil material.

LITERATURE REVIEW

The purpose of the literature review has been to cover those articles which have a direct bearing on the study rather than to cover all aspects of saturated flow.

The classic equation of water movement set forth by Henry Darcy (1856) has occupied a unique place in the study of fluid flow through porous media. Darcy's flow may be written as

$$v = Ki \tag{1}$$

where v is the macroscopic flow velocity, K is the hydraulic conductivity and i is the hydraulic gradient. Following Richards (1952), K itself is written as

$$K = kgp/\eta \tag{2}$$

where k is the intrinsic permeability, η is the fluid viscosity, p is the fluid density and g is the acceleration of gravity.

The proportionality between flow velocity and hydraulic gradient [equation (1)] is the condition of linearity which combines with the law of conservation of mass to yield the Lapace heat-type or diffusion type equations. This enables conventional methods of mathematical physics to be used for describing flow through porous media.

Darcy recognized that his relationship was not valid for high fluid velocities. During the past forty years, much research has been

concerned with the nature of this deviation, which occurs at large hydraulic gradients (Muskat 1946, Scheidegger 1960). It seems well established that when the hydraulic gradient exceeds a critical value, the flow velocity is no longer proportional to the hydraulic gradient but increases less rapidly than the gradient. This could be accounted for since viscous forces no longer mask the inertia and turbulence forces and not all of the driving force of the hydraulic gradient is used to overcome viscous resistance.

Compared with the extensive study conducted on deviations at large gradients, much less work has been directed toward the testing of Darcy's law for liquid flow at low gradients, even in soils where such flow is common. Hubbert (1940) indicated that there was no apparent reason to suspect failure at low gradients. However, Scheidegger (1960) recognized the possibility of deviations arising from the so-called "boundary effect," from ions in solution and from non-Newtonian fluids.

Until recently, Darcy's law was believed to be valid over the complete range of hydraulic gradients. During the fifties, the reports of Lutz and Kemper (1959) and Schmid (1957) suggested that Darcy's law is not valid at low hydraulic gradients. Instead of velocity being directly proportional to hydraulic gradient i, a non-linear relationship of the kind shown in Figure 1 was found at the low hydraulic gradients. A feature of these reports was that there exists a magnitude of the hydraulic gradient i_c, referred to as the critical hydraulic gradient, such that the discharge velocity is zero unless the applied hydraulic gradient is greater than i_c.

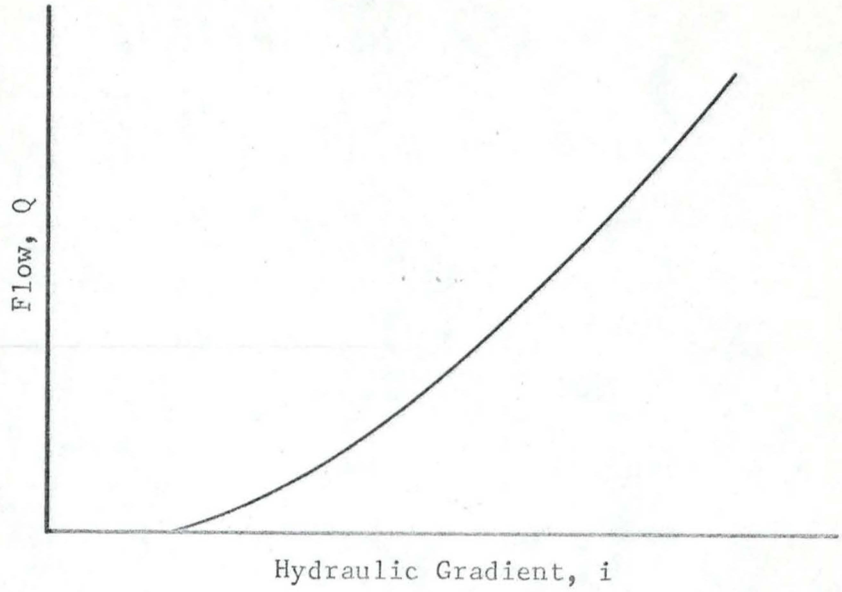

Figure 1. Non-linear relationship at low hydraulic gradients.

(after Kraft and Yaakobi 1966)

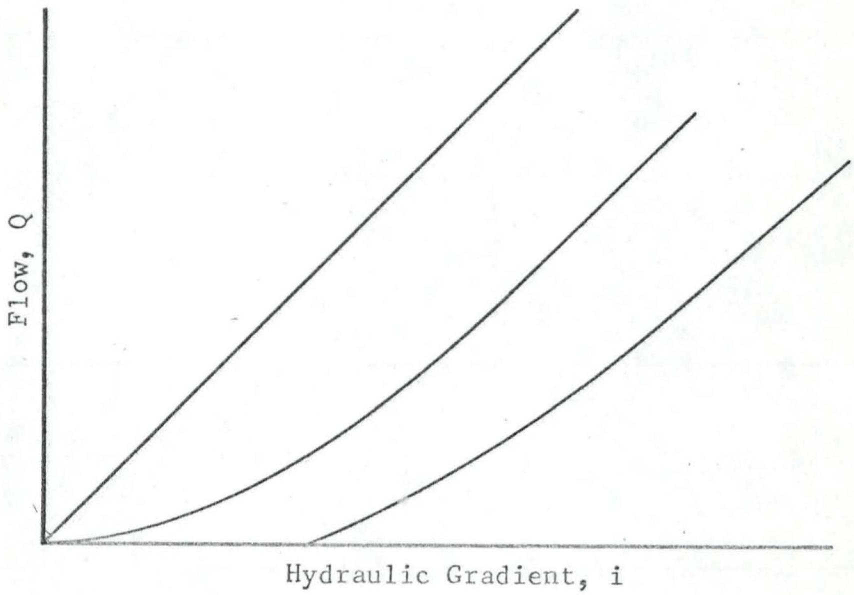

Figure 2. Discharge curves at low hydraulic gradients.

(after Kraft and Yaakobi 1966)

Mathematical work started before 1963 to incorporate non-Darcy behavior into the mathematical equations of fluid flow through a porous media (Gheorghitza 1963). An examination of the recent work concerning non-Darcy behavior revealed that its existence is not firmly supported by experiments. In addition, there is little agreement as to the theoretical explanation for non-Darcy phenomena.

All of this is seen in experiments which were directly aimed at investigating flow in clay soils at low hydraulic gradients (Hansbo 1960, Miller and Low 1963, Li 1963, and Olsen 1965). The type of discharge curve that each of the investigators found is shown in Figure 2. Besides the seemingly inconsistency of their findings, there are several aspects of these experiments which indicate the need for further improvement in experimental details and more clarification as to which physical quantities are to be measured.

Olsen (1966) reviewed the problems associated with the conventional measuring technique that is used in determining the hydraulic conductivity of saturated clays. He also described a new technique in which these problems were avoided. With the new technique, a known flow rate through the clay sample was produced while the head difference induced across the sample was measured. Known constant flow rates were produced by driving the plunger of a syringe at constant rates with a multispeed syringe pump. The applied flow rates and the measured head differences were not affected by the air-water meniscuses using the new technique and the time intervals needed to obtain head difference measurements were shortened. Data obtained with this new

technique showed the validity of Darcy's law in kaolinite over a wide range of porosities at low gradients.

The conventional laboratory technique for determining the hydraulic conductivity consists essentially of (1) placing a clay sample in a test cell connected in series with a capillary tube containing an air-water meniscus or an air bubble, (2) producing flow through the clay with a known hydraulic head difference across the test cell-capillary tube system, and (3) determining the induced flow rate from measurements of the rate at which the meniscus or air bubble moves through the capillary tube (Olsen 1966). The hydraulic conductivity (K) is calculated from the applied head difference (Δh), the induced flow rate (Q/t), length (l), and the cross-sectional area (A) of the sample, using Darcy's law

$$Q/t = KiA \tag{3}$$

where i is the hydraulic gradient and equals $\Delta h/l$.

The principal difficulties with this technique arise from contaminants present in the apparatus and from the long times and/or high gradients required to obtain measurable flow rates. Contamination gives rise to an error in the calculation of the head difference across the clay sample. Olsen (1965) concluded that atmospheric contamination in flow rate measuring capillary tubes can cause false deviations in the data of Hansbo (1960). Hansbo's data therefore appear to be evidence of Darcy behavior in confined samples of natural illitic clays that were tested at gradients ranging from 1-10.

Miller and Low (1963) observed deviations in confined samples of montmorillonite that occurred over both low and high ranges of gradients. The principal deviations appear at gradients in the range from 0 to 100. Olsen's (1965) study showed that only part of these deviations can be attributed to the atmospheric contamination error that accounted for Hansbo's deviations. This error results from inaccurate corrections for pressure differences across air-water meniscuses in contaminated capillary tubes. The contamination error was negligible in comparison with the observed deviations in the unconfined clay and sandstone samples of Lutz and Kemper (1959) and Von Englehardt and Tunn (1955). Another possible error that could be present in the test cell-capillary tube system is in the inaccurate flow rate measurements due to the movement of liquid around the air bubbles of the capillary tubes.

When hydraulic conductivities are determined using low applied gradients, periods of hours or days are often required to obtain measurable movements of meniscuses in the capillary tube. Precautions must be taken to avoid false movements of the meniscuses due to volume changes in the sample, the capillary tube, connecting channels, fittings, and tubing. The sample must be rigidly confined to avoid creeping with subsequent consolidation or expansion. Rigorous temperature control is needed to avoid expansion and contraction of the apparatus.

Some investigators have minimized these difficulties by employing relatively high gradients to obtain more rapid flow rates. Although this method shortens measurement time and reduces the temperature control requirement, it introduces another complication. Large seepage

forces may alter the arrangement of particles within a clay sample in ways that do not occur under the much smaller seepage forces associated with the usual low gradients in clay bearing sediments.

King (1898) reported for low gradients in various porous media that the flow velocity was not proportional to the gradient. Instead, the velocity increased more than proportionally with the gradient. This was in contrast to the less-than-proportional increases at high gradients of which King was well aware.

The flow media used by King included tube-confined brass-wire gauze discs, sand, sandstone, and ordinary glass capillaries. For all of these he reported greater-than-proportional increases for flow velocity versus gradient. His evidence for the capillary tubes is perhaps the least convincing. Not only were the deviations small, but they essentially disappeared when evaporation from the outflow water droplets was prevented. When King's results are expressed in terms of hydraulic gradient, Darcy's law, for all practical purposes, is verified even though King's detailed calculations indicated a departure. In much of King's data there is evidence that, at constant gradient and temperature, his systems were subject to flow reduction with time. As reported by Gupta and Swartzendruber (1962) this response might have been caused by bacterial activity.

Kraft and Yaakobi (1966) gave a theoretical deviation of Darcy's law. The derivation was a guide as to what physical quantities should be measured in experiments used to determine permeability.

Klausner and Kraft (1966) proposed a model for non-Darcy behavior that assumes an ordinary Newtonian fluid is imagined to be flowing in an ensemble of parallel capillaries of circular cross section with steady Poiseuille flow. The wall of each capillary exerts a force (Chapman-Gouy crystal force) on the fluid (Kryt 1952). This force F is perpendicular to the flow velocity which is along the tube axis and therefore cannot do work on the fluid. F is taken into account by assuming that it brings into action a second plastic type force f (wall force) acting along the tube axis and opposing the flow. With these assumptions it is shown mathematically that, depending on the porosity of the model and the wall force magnitude, the model's discharge curves can have any of the shapes shown in Figure 2 (Kraft and Yaakobi 1966). A group of discharge curves for a Chapman-Gouy type wall force is shown for varying porosity in Figure 3. The model shows a remarkable similarity to the intuitive description of non-Darcy flow given by Miller and Low (1963).

Kraft and Yaakobi (1966) suggested that when future permeability tests are made they cover a wide range of different porosities and clay types with varying Chapman-Gouy potentials.

Three types of flow behavior are demonstrated in Figures 4 and 5. Newtonian flow is shown as a straight line passing through the origin. This type of flow is present when the viscosity of the liquid is constant with respect to different hydraulic gradients. For non-Newtonian flow, the curve passes through the origin but is no longer

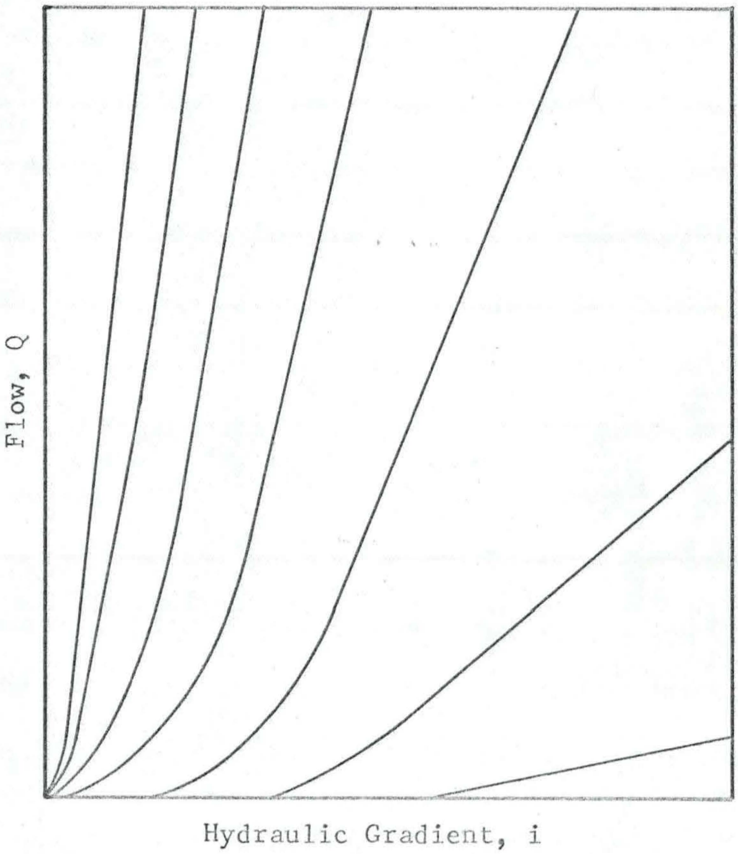

Figure 3. Discharge curves for Chapman-Gouy force.

(after Kraft and Yaakobi 1966)

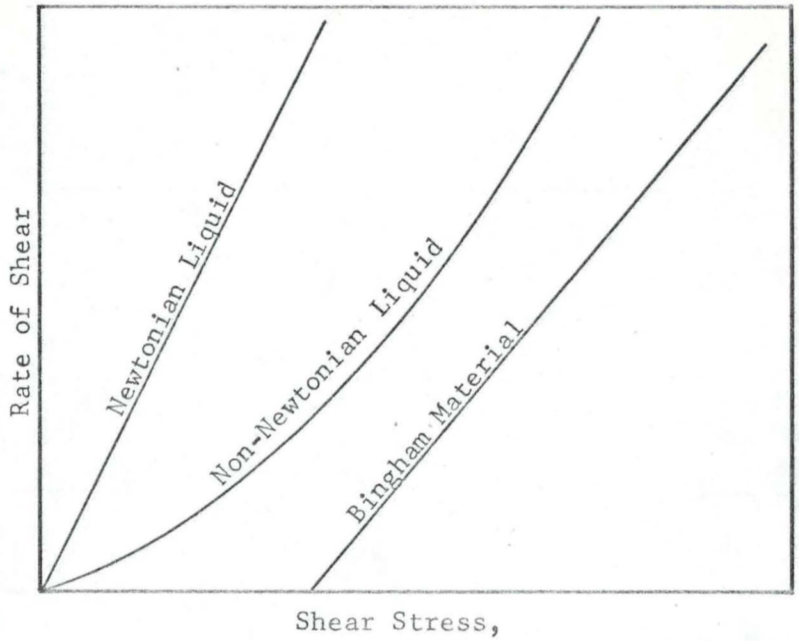

Figure 4. Shear rate versus shear stress.

(after Swartzendruber 1962a)

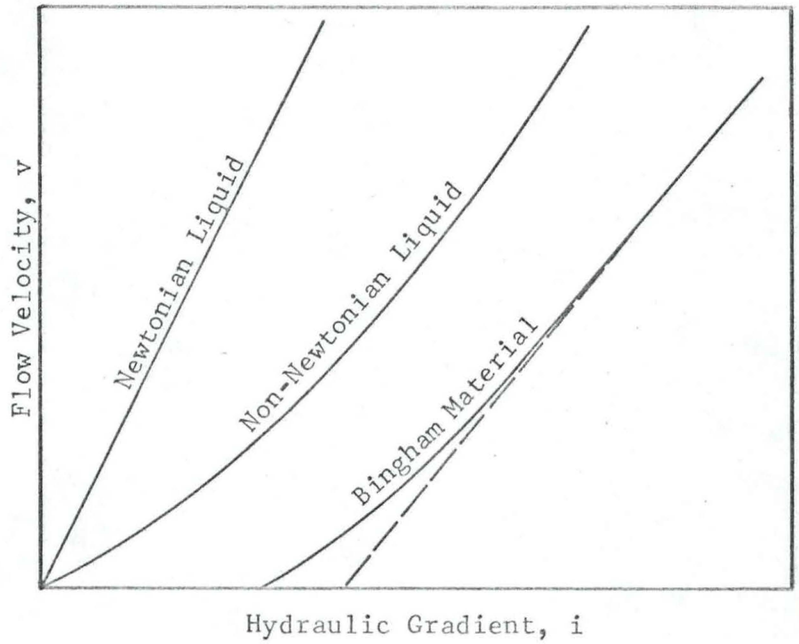

Figure 5. Flow velocity versus gradient.

(after Swartzendruber 1962a)

straight. For Bingham flow, the curve is linear but only for shear stress in excess of the yield stress.

The assertion of Darcy's law is analogous to the graph of the Newtonian liquid (Figure 5). If the flow is not Newtonian, it is then either non-Newtonian or Bingham. Von Englehardt and Tunn (1955) and Low (1961) suggested the possibility of non-Newtonian behavior but they did not propose a mathematical expression.

The straight lines produced by sand and sandstone in King's (1898) work are suggestive of the straight-line asymptote of the Bingham curve in Figure 5. These lines could conceivably bend through the origin if the necessary experimental points were available. The data of Von Englehardt and Tunn (1955), Lutz and Kemper (1959), and Hansbo (1960) indicate that such curvature does occur, which is suggestive of non-Newtonian flow (Figure 5). While recognizing that threshold gradients have been reported for ceramic and charcoal filters, Derjaguin and Krylou (1944) and Swartzendruber (1962a) felt that adequate experimental proof of such gradients for sandstones and clays is, as yet, lacking. It is then conjectured that the qualitative aspects of Hansbo's (1960) approach are, at present, the most reasonable (Swartzendruber 1962a). These are shown in Figure 6 by the solid-line curve which begins at the origin, bends upward and then approaches a straight line which extrapolates to an i-intercept designated by I. This choice of curve combines the origin and curvature aspects of non-Newtonian flow with the straight-line aspect of Bingham flow. By the gradient range in Figure 6, it is assumed that deviations due to inertia and turbulence do not appear.

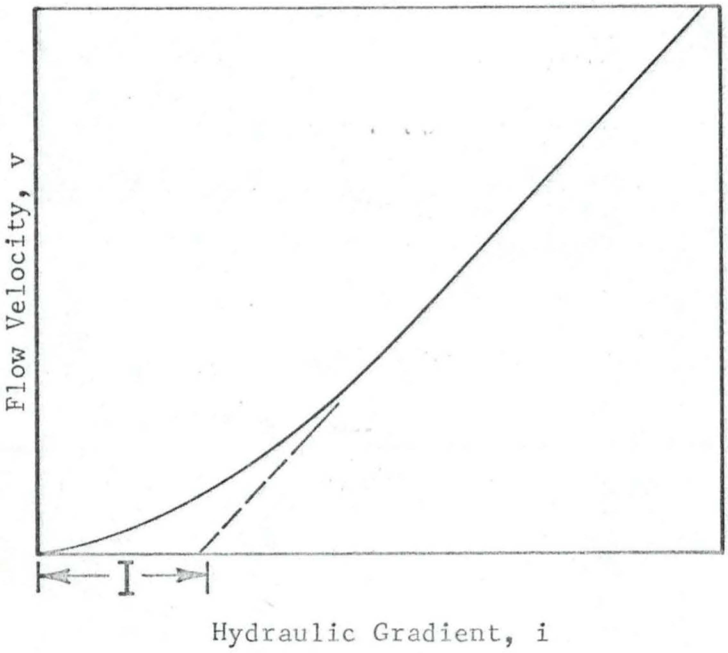

Figure 6. General aspects of the non-linear flow relationship.

(after Swartzendruber 1962a)

Swartzendruber (1962b) gives three reasons for reconsidering the question of the validity of Darcy's law. First, there is the data of Von Englehardt and Tunn (1955, Lutz and Kemper (1959), and Hansbo (1960) which do not obey Darcy's law, at least from the phenomenological standpoint represented by velocity-gradient curves. Secondly, there is increasing evidence that water properties near clay surfaces are not the same as those of normal bulk water (Low 1960, 1961). Finally, the work of King (1898), who considered such deviations more than sixty years ago, seems largely to have been ignored.

Hansbo suggested that the curved part of Figure 6 is represented mathematically by a power function and that this be replaced by a linear function when the curve has straightened out. Three independent parameters or constants are required with this approach. While the two mathematical forms are a complication, a worse drawback is that the three parameters cannot be evaluated unless data are available all the way from $i = 0$ out to and including an appreciable part of the linear portion of the velocity-gradient curve.

To circumvent these difficulties, Swartzendruber (1962a) proposed the relationship

$$dv/di = M(1-e^{-1/I}) \tag{4}$$

where M and I are constants, v is the macroscopic flow velocity, and i is the hydraulic gradient. Integrating and using $v = 0$ at $i = 0$ (for non-Newtonian flow) leads to

$$v = M[i - I(1 - e^{-i/I})] \tag{5}$$

which then is the modified flow equation that appears to fit the published data of several investigators (Von Englehardt and Tunn 1955, Lutz and Kemper 1959, Hansbo 1960, and Low 1960).

As i increases in equation (5), $e^{-i/I}$ approaches zero, with the result

$$v = M(i - I) \tag{6}$$

which is the equation of a straight line of slope M and i-intercept I.

Due to the similarity between M and K [equations (1) and (6)], M is partitioned in the manner of Richards (1952) by writing

$$M = mpq/\eta_l \tag{7}$$

where m is determined by particle geometry and η_l is the normal bulk viscosity of the liquid. In order to avoid confusion with Darcy's law, M = K could be called the hydraulic conductance and m = k, the permeance.

For the sandstones of Von Englehardt and Tunn (1955), equation (7) was used to calculate m-values. Swartzendruber values (1962a) always exceeded the liquid k_{max} values of Darcy's law as would be expected since Darcy's law presumes a straight line through the origin for v versus i. The m-values were always less than the air permeability since some particle rearrangement might be expected when the clay-bearing sandstone was wetted with water or salt solution. In every case, m increased with salt concentration. This could be expected since, for higher salt concentrations, the clay should be less subject to deflocculation and dispersion.

With one exception, I decreased as the salt concentration increased. This implied that pure water exhibited the greatest degree of non-Newtonian behavior since I is a measure of non-Newtonian behavior (Swartzendruber 1962a).

METHODS

The water transmission characteristics of confined montmorillonite clay subsoil material of the Springerville and Brolliar soil series were investigated. The soil materials were obtained from the 24-30 inch depth. A general description of the soils is given by Williams and Anderson (1967). Physical and chemical analyses of the soil materials were made as described in A Study to Determine the Hydrologic and Physical Properties of Some Beaver Creek Soils (Watershed Management Dept. 1968).

A description of the system used to measure the flow of water through saturated, confined clay soil is given in Figure 7. The apparatus consisted of a mercury manometer (17), pressure transducer (18), multispeed syringe pump, deairing flask (16), and confined soil core (7).

The manometer was used to measure the hydraulic pressure when a steady flow rate had been obtained. A pressure transducer with a strip chart recorder was used to determine when steady state conditions were reached. The transducer was a Sanborn model 267 BC which was operated with a Sanborn model 311A Transducer Amplifier-Indicator. The output was monitored with a Leeds and Northrup Company model W recorder.

A Harvard Apparatus Company model 600-901 syringe pump was used to produce fixed flow rates through the soil core (7) by driving the plunger of a hypodermic syringe at constant rates with the multispeed

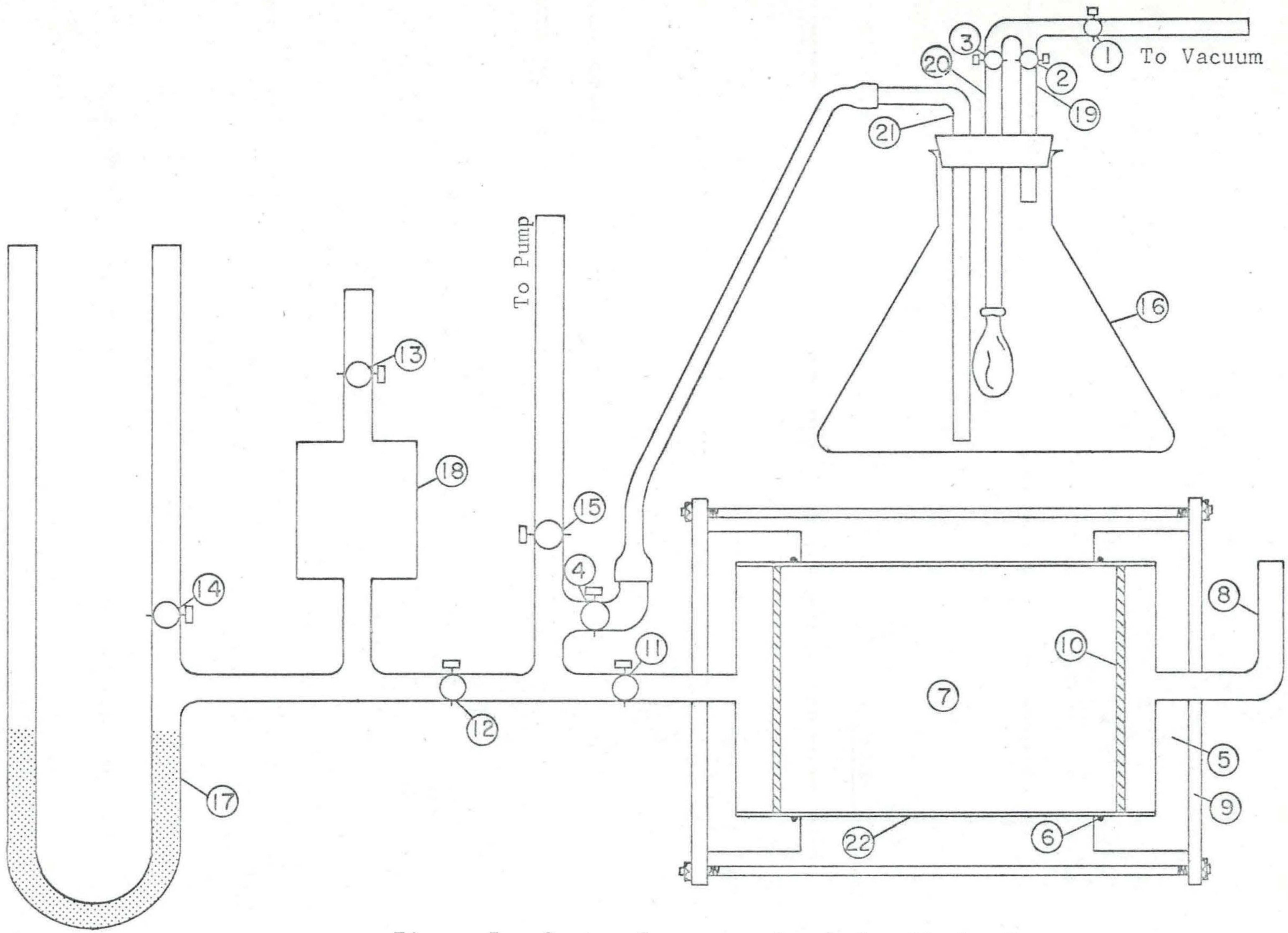

Figure 7. System for measuring hydraulic head.

syringe pump. Hamilton gas-tight syringes were used with the pump. The pump moved the syringe plunger by means of a worm gear driven by a synchronous motor through a transmission box. The gear selector on the pump enabled the syringe plunger to be driven at 12 speeds ranging from 1×10^{-1} to 2×10^{-5} cm/sec. The flow rates for the different gear speeds and different sizes of syringes were determined from charts supplied with the pump. The flow rates per unit cross section of soil core used in the study ranged from 0.0325×10^{-3} to 12.0×10^{-3} cm/min.

When measuring the flow of water through saturated soils, a major difficulty is the exclusion of air, both from the soil and from the hydraulic system (Christiansen 1944, Pillsbury and Appleman 1945). To eliminate this problem, deaired water has commonly been used in obtaining a saturated soil without entrapped air as discussed by Bertran (1940), Pillsbury and Appleman (1945), Lambe (1951), and Li (1963). Throughout each run, the system was deaired and protected from air diffusion. This feature was important for accurate measurement because if the permeating fluid was airborne even to the slightest degree, air would then be released on its passage through the clay, thus blocking the water channels. Deaired water would also tend to dissolve any free air present in the saturated soil.

The deairing apparatus is shown in Figure 7. The apparatus was designed similar to one described by Yevnin (1967). The deaired water for the cell was prepared and stored in a 500-ml Erlenmeyer vacuum flask. Two copper tubes with pressure fittings and one plastic tube were passed through the rubber stopper which was cemented to the opening

in the top of the flask. Tube (19), which was connected to the water source, was used for filling the flask. Tube (20) was connected to a rubber bladder within the flask, and tube (21) was connected to the outlet for the deaired water. Tubes (19) and (20) were connected to the vacuum pump by way of valve (1).

Water was deaired under a vacuum of 65 mm of mercury. To deair the water in the flask, the bladder was first evacuated and then valve (3) was closed. Valve (2) was then opened and a vacuum was applied and maintained until mo more bubbles issued from the water. Valve (2) was then closed. Valve (1) was kept open and valve (4) closed during these operations. If water was not to be taken from the flask within a short period of time, the bladder and the flask were re-evacuated to prevent air from dissolving in the water.

The amount of air in the deaired water was not determined. However, the fact that at the first evacuation air bubbled out profusely, while subsequent applications of vacuum created few or no bubbles, shows that the low air content in the water was maintained.

The flow assembly consisted of two aluminum caps (5) with "O" rings (6) to seal the brass sample ring (22). The brass ring was 3.0 cm long and 7.3 cm in diameter. Fritted glass bead plates (10) were used to insure even distribution of water across the core ends. One layer of coarse filter paper was placed between the porous plate and core ends to prevent soil particles from clogging the porous plates. The top of the outlet tube (8) was at the same height as the top of the brass ring to keep the soil completely saturated. The cell was

mounted in a channel aluminum frame (9) and clamped to maintain soil core volume.

In order to pack the soil in the cell, the brass ring was first installed in one of the aluminum caps. The air-dried soil was packed in the ring at as uniform a bulk density as possible. By knowing the weight of the soil placed in the brass ring and the volume of the ring, the bulk density of the soil core could be estimated. The porosity of the soil core was calculated by assuming a soil particle density of 2.72 g/cm^3.

The frame and cell were placed in a horizontal position to eliminate the effects of gravity on the flow of water through the cell. The soil was saturated and air was flushed from the cell by pumping deaired water through the soil core and cell at the rate of 0.294×10^{-3} cm/min per unit cross section of the soil core. It took about 7 days to deair and saturate the soil core. The actual time depended on the bulk density of the core and the amount of entrapped air within the cell. When the pressure remained constant for 48 hours, the soil was assumed to be saturated and the swelling pressure constant.

Before starting a run, the distilled water was deaired and then allowed to come to room temperature. To transfer deaired water from the flask (16) to the pump, air was allowed to enter the bladder by opening valves (1) and (3). Valves (4) and (15) were then opened and (11) and (12) were closed. Valves (13) and (14) were open to allow air to escape from the transducer and manometer, respectively. They were closed when a run was in progress. Valve (4) was closed and valves

(11), (12), and (15) were open during a run. When the pressure for a certain flow rate had become constant, the pressure was noted and the next higher flow rate was started. The pressure for each flow rate was multiplied by a correction factor of 0.93 which took into account the pressure effect that the water had on the level of mercury in the manometer. The relationship

$$1 - \frac{\text{density of water}}{\text{density of mercury}} \tag{8}$$

was used to determine the correction factor. Four runs were made for each soil at each given bulk density. The hydraulic pressure was divided by the length of the soil core in order to determine the hydraulic gradient necessary to produce a fixed flow rate.

RESULTS AND ANALYSIS

The average hydraulic gradient for the fixed flow rates of the four runs for each soil at each porosity are given in Tables 1-A and 2-A of the Appendix. The data are plotted in Figures 8 through 19. The experimental points are shown in the figures as circles. The solid-curve line is the data fitted to equation (5). Two features of the relationship of flow to hydraulic gradient are evident in these figures: (1) the extremely low permeability rates for both soils at all porosities and hydraulic gradients, and (2) the non-linearity of the flow-hydraulic gradient relationship.

Although both soils have low permeability, the Brolliar soil material at the higher porosity was considerably more permeable than the Springerville material. As porosity decreased, the difference in permeability between the two soils decreased. The low permeabilities found in these materials have important implications to watershed management. For example, a soil column three feet thick with a porosity of 49.6%, which had a one-half inch of water maintained on its surface, such as might occur during snow melt, would transmit only about 4.4 gallons of water per day per acre of subsoil material. Only about 7.1 gallons of water per day per acre would be transmitted by the more permeable Brolliar subsoil material. This points up the controlling influence that the low permeability of these subsoils play in the hydrologic behavior of watersheds where they are located. The contribution to

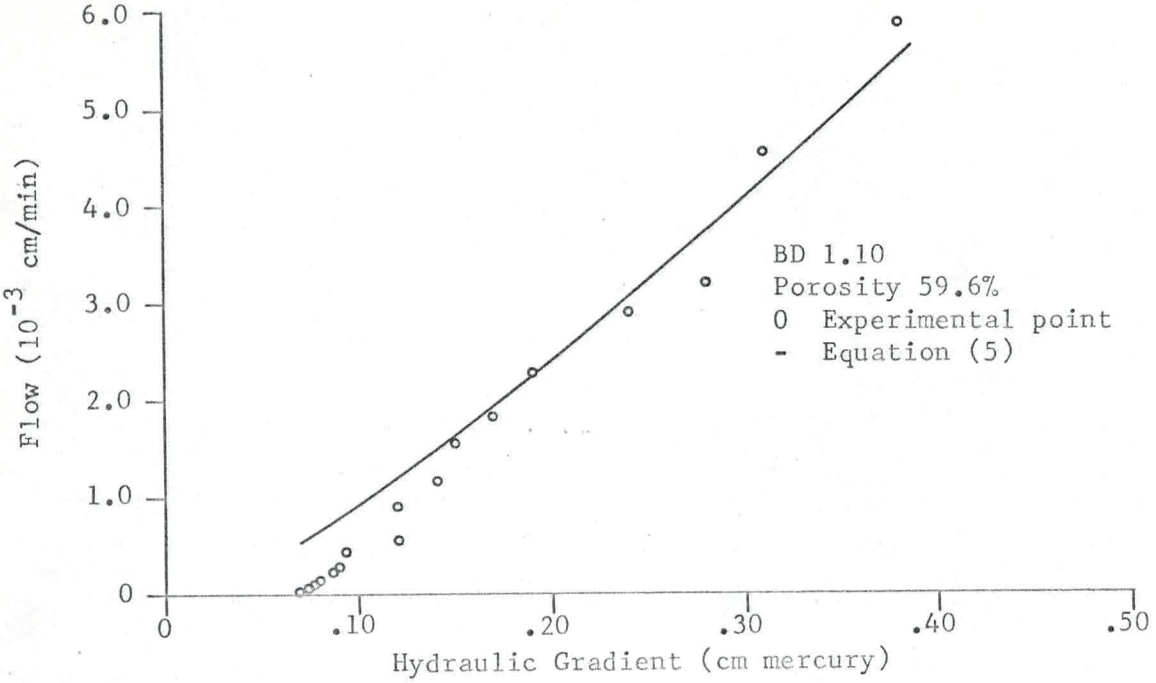

Figure 8. Flow rate versus hydraulic gradient for Springerville soil (BD 1.10).

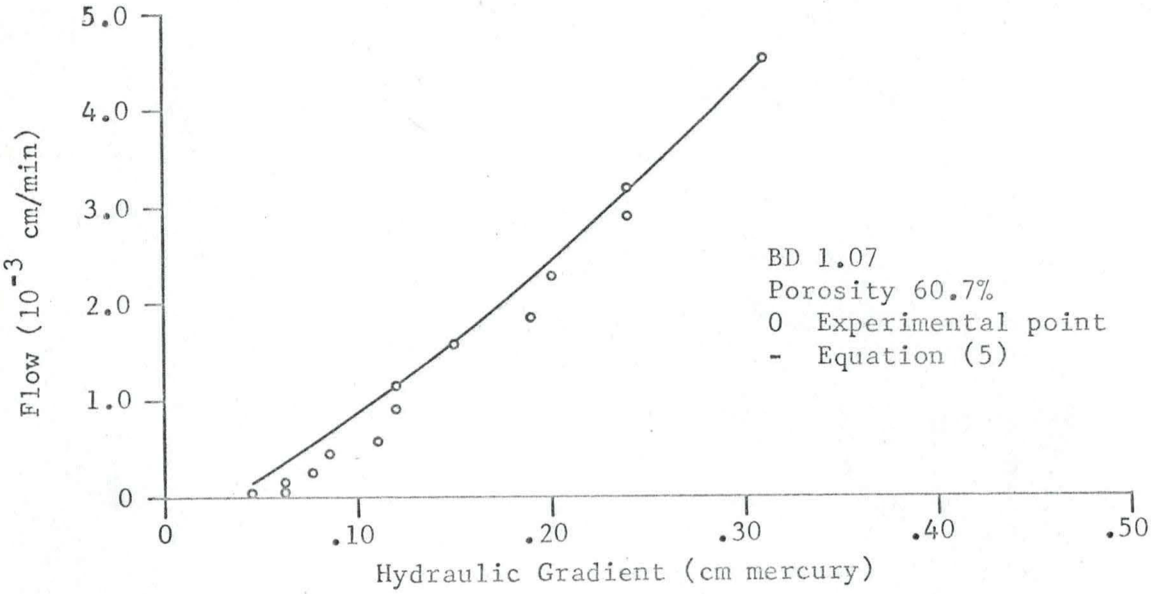

Figure 9. Flow rate versus hydraulic gradient for Brolliar soil (BD 1.07).

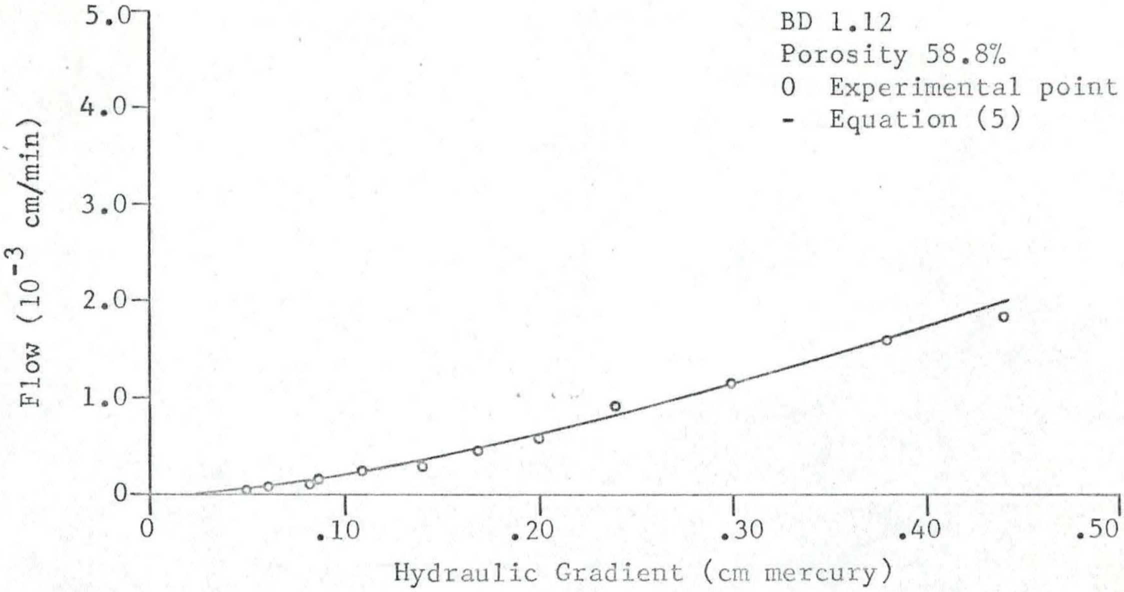

Figure 10. Flow rate versus hydraulic gradient for Brolliar soil (BD 1.12)

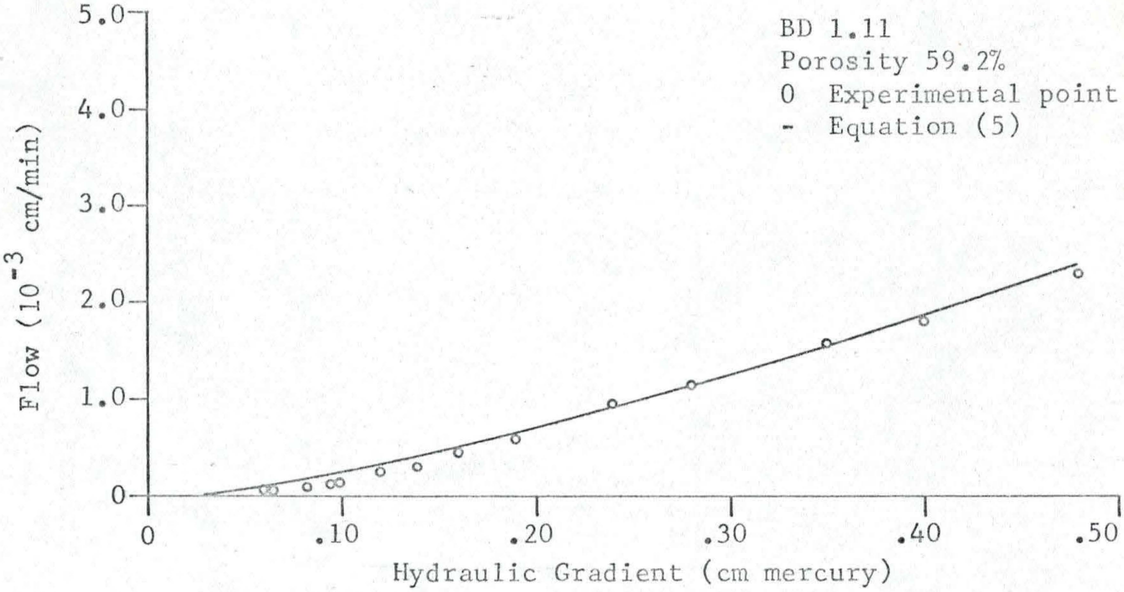

Figure 11. Flow rate versus hydraulic gradient for Brolliar soil (BD 1.11)

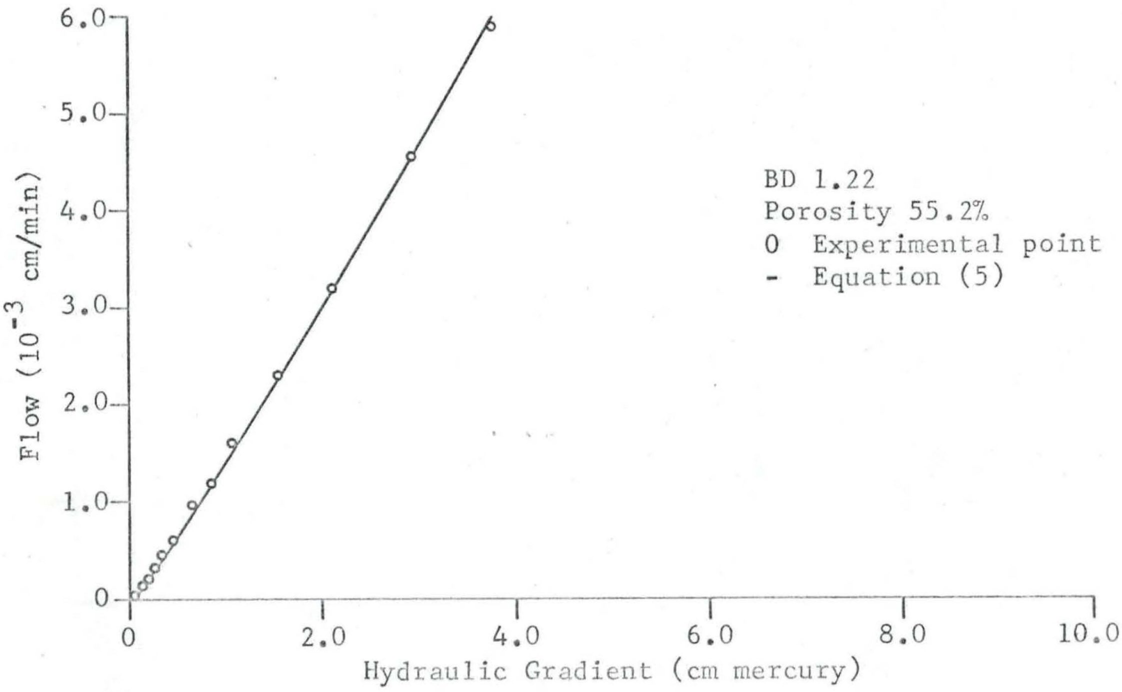

Figure 12. Flow rate versus hydraulic gradient for Springerville soil (BD 1.22).

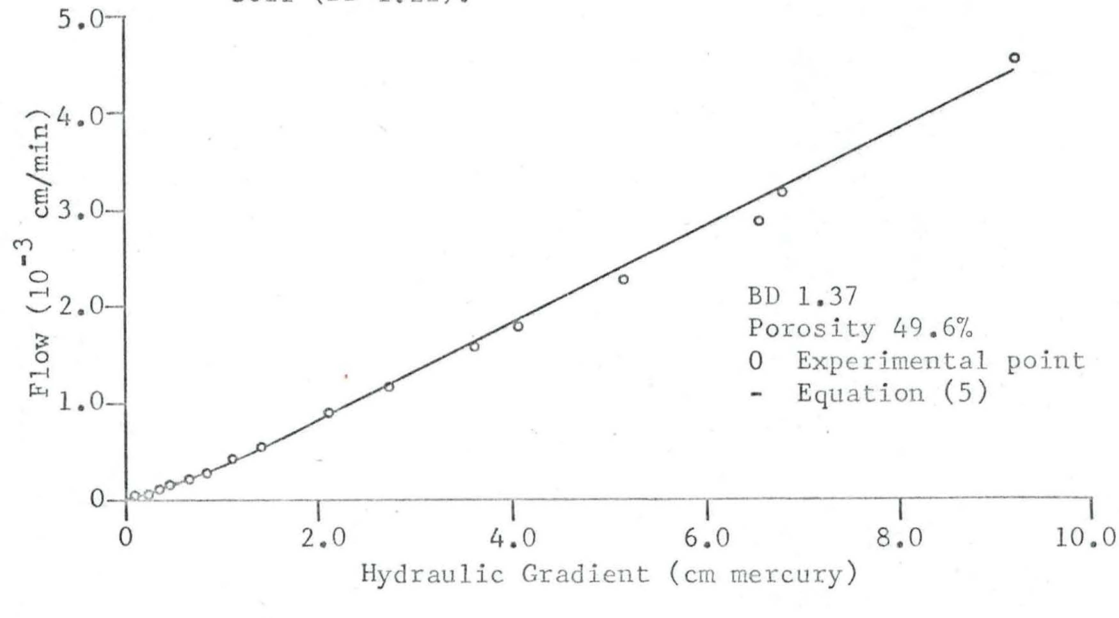

Figure 13. Flow rate versus hydraulic gradient for Brolliar soil (BD 1.37).

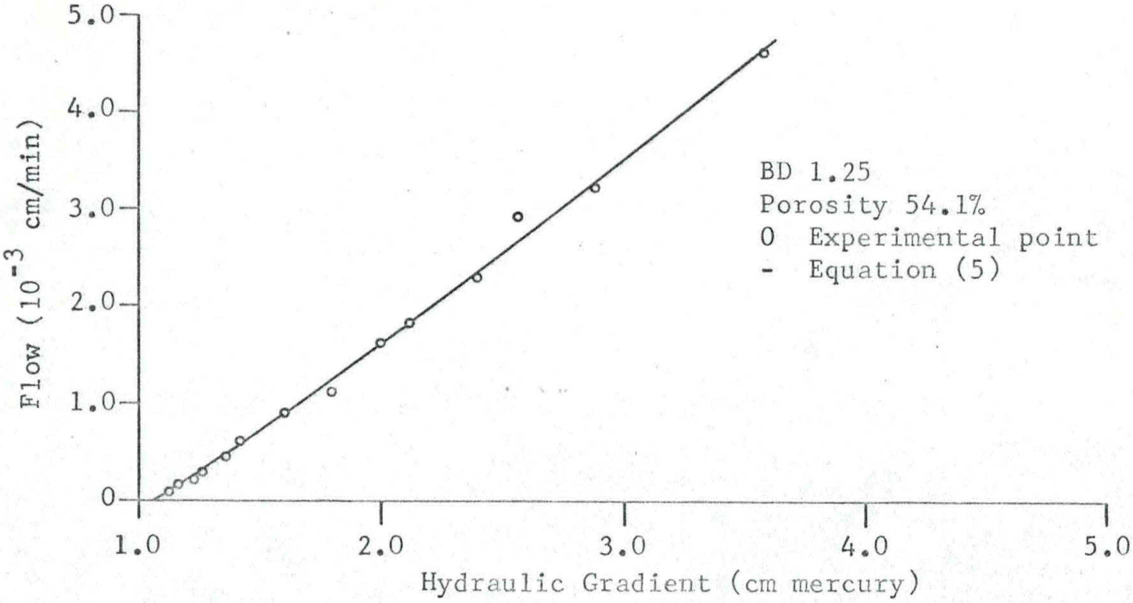

Figure 14. Flow rate versus hydraulic gradient for Brolliar soil (BD 1.25).

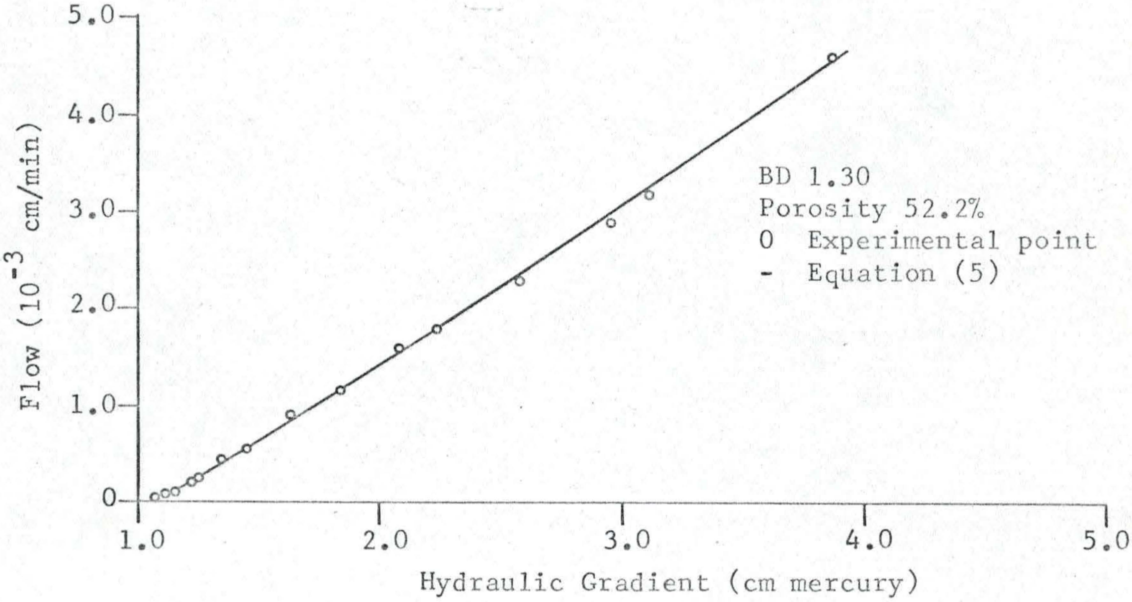

Figure 15. Flow rate versus hydraulic gradient for Springerville soil (BD 1.30).

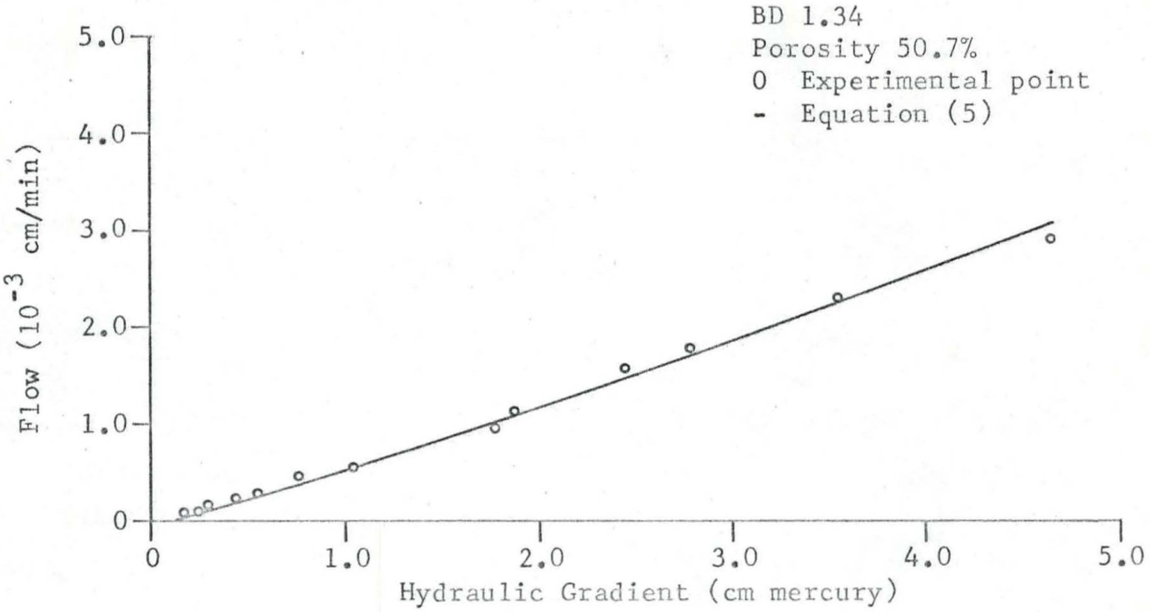

Figure 16. Flow rate versus hydraulic gradient for Springerville soil (BD 1.34)

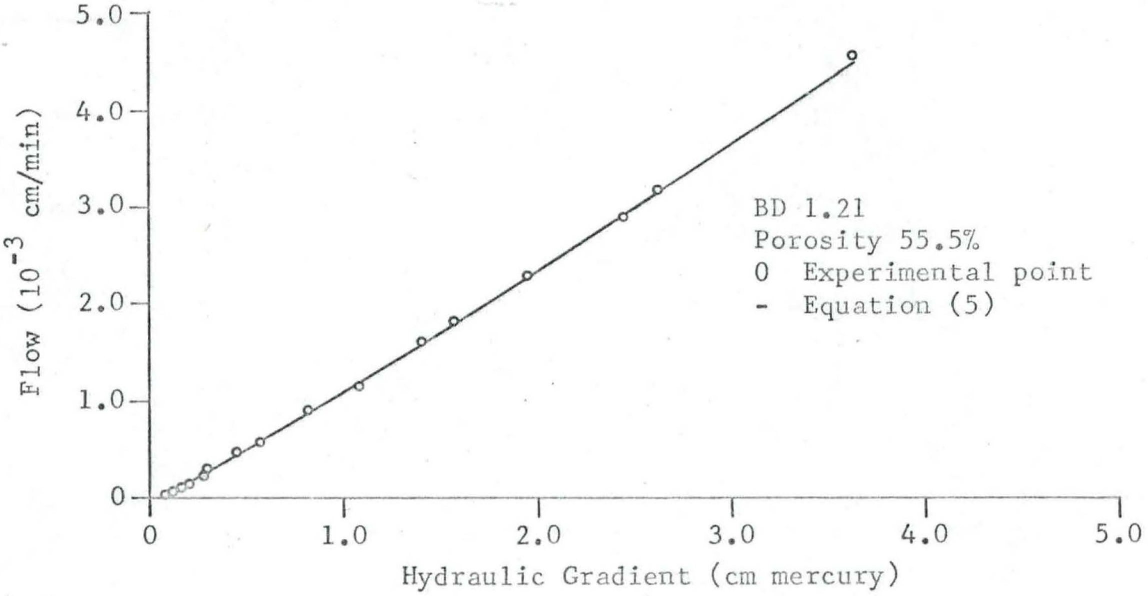

Figure 17. Flow rate versus hydraulic gradient for Springerville soil (BD 1.21).

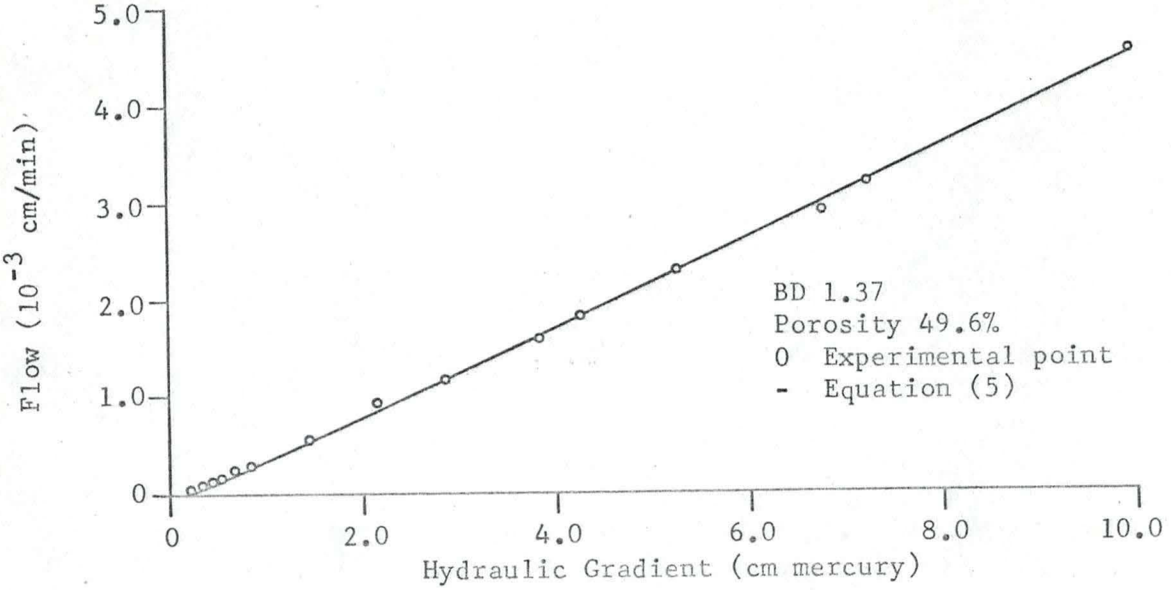

Figure 18. Flow rate versus hydraulic gradient for Springerville soil (BD 1.37)

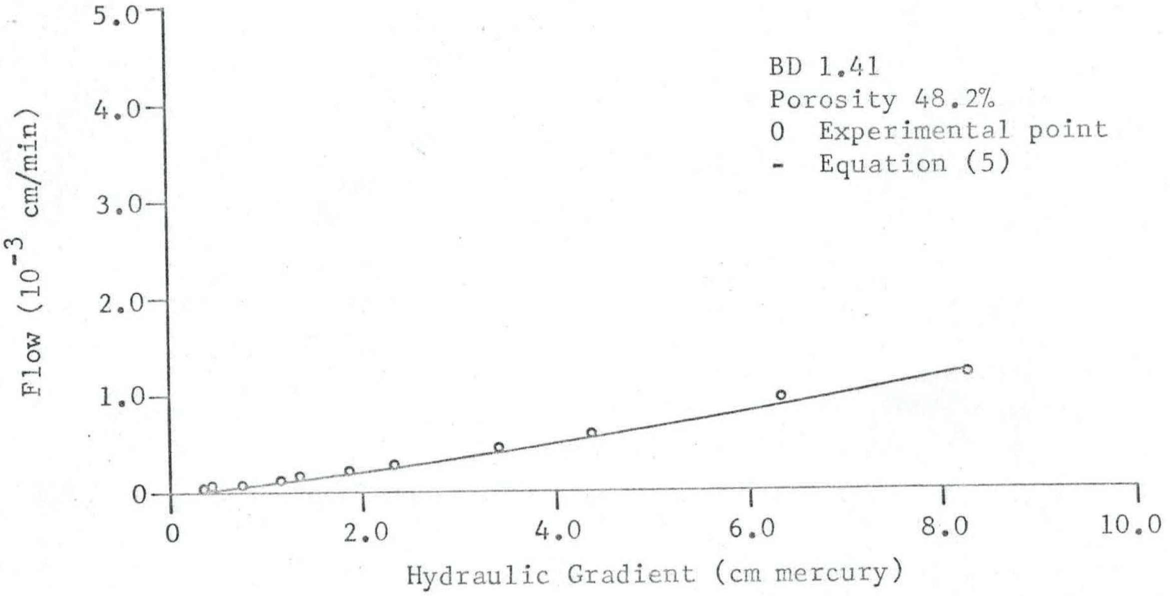

Figure 19. Flow rate versus hydraulic gradient for Springerville soil (BD 1.41)

base flow from the watersheds would be very small and delayed only over a short period of time. The predominance of ephemeral streams of the Beaver Creek area are evidence of this effect.

Non-linearity between flow and hydraulic gradients were pronounced at very low gradients. Flow rates increased at a more than proportional increase with the hydraulic gradient for both soils. A linear or straight line relationship between flow rates and hydraulic gradients existed only at the higher gradients. Thus, Darcy's equation does not strictly apply in describing the flow of water through these soil materials.

Because Darcy's equation, namely, equation (1), does not apply to the conditions of this study, the data were fitted to Swartzendruber's (1962a) modified flow equation

$$v = M[i-I(1-e^{-i/I})] \qquad (5)$$

Swartzendruber (1962a) assumed that the hydraulic gradient range involved is below that at which kinetic or turbulence effects appear. As i increases in equation (5), $e^{-i/I}$ approaches zero, with the result

$$v = M(i-I) \qquad (6)$$

which is the equation of a straight line of slope M and i-intercept I.

Equation (5) is a two-parameter expression which apparently possesses the behavior of Figure 6. It must be noted that I is not a threshold gradient. Instead it is an extrapolated intercept and is a measure of non-Newtonian or non-Darcy behavior. It is also the only

measurement of departure from proportionality in equation (5). When $I = 0$, the behavior is Newtonian, and equation (5) reduces to Darcy's law where M is equivalent to K in equation (1). It imposes the somewhat restrictive requirement that the slope of the velocity-gradient curve always be zero at $i = 0$, regardless of the size of I, unless $I = 0$. Thus, Swartzendruber's equation is a compatible modification of Darcy's equation in that Darcy's law is included as a special case when the flow behavior is linear or Newtonian. It provides two parameters to describe the flow of water and ionic solutions in the presence of clay. In the past, all such description has of necessity been forced into the single Darcy parameter.

The I parameter in equation (5) is defined as the straight-line asymptote of Swartzendruber's (1962a) modified flow equation. I was determined for each soil by running a linear regression of the form

$$Y = b_o + b_1 X_1 \tag{9}$$

on the data obtained for the higher hydraulic gradients and solving for the hydraulic gradient (X) at zero flow ($Y = 0$).

Equation (6) was used to determine the value of the M parameter. The equation was rearranged in the form

$$M = \frac{\bar{v}}{(\bar{i} - I)} \tag{10}$$

where $\bar{v}$ and $\bar{i}$ are the mean flow velocity per unit cross section of soil core and mean hydraulic gradient, respectively. They were determined from the linear portion of the flow-hydraulic gradient relationship.

The values for I were calculated as above. After the two parameters (I and M) had been determined, they were adjusted as suggested by Swartzendruber (1962a), in order that equation (5) would give a greater emphasis to the experimental points derived at the lower gradients. The values for I and M are given in Tables 1 and 2.

The relationship of I to soil porosity for both soils is shown in Figures 20 and 21. Both linear and quadratic functions were fitted to the data by regression analysis. Equation (9) was used for linear regression and the equation

$$Y = b_o + b_1X_1 + b_2(X_1)^2 \tag{11}$$

was used for curve linear regression. The R^2 values for linear regression were .80 and .92 for the Springerville and Brolliar subsoil materials, respectively. For curve linear regression the R^2 values were .94 and .98, respectively. The quadratic equation fitted the data significantly better than did the linear equation.

Figure 20 indicates that as porosity increases, flow behavior becomes more nearly Darcy-like since the I parameter becomes increasingly smaller as porosity increases. The rate at which I approaches zero varies between the two soil materials. Interestingly, the I values for the Brolliar soil, which has the generally higher permeability, are greater than the I values for the less permeable Springerville material. Thus, the Brolliar material has a flow behavior that is more non-Darcy than the Springerville materials. These contrasting features could be caused by the sodium and clay content of the soils presented in the Discussion section.

Table 1. I and M parameters for Springerville subsoil material.

BD (g/cm^3)	Porosity (%)	I	M
1.10	59.6	.040	.0154
1.21	55.5	.067	.00125
1.22	55.2	.083	.0016
1.30	52.2	.100	.00164
1.34	50.7	.130	.00069
1.37	49.6	.177	.00046
1.41	48.2	.267	.00015

Table 2. I and M parameters for Brolliar subsoil material.

BD (g/cm^3)	Porosity (%)	I	M
1.07	60.7	.067	.0183
1.11	59.2	.097	.0064
1.12	58.8	.083	.0056
1.25	54.1	.133	.0019
1.37	49.6	.267	.0005

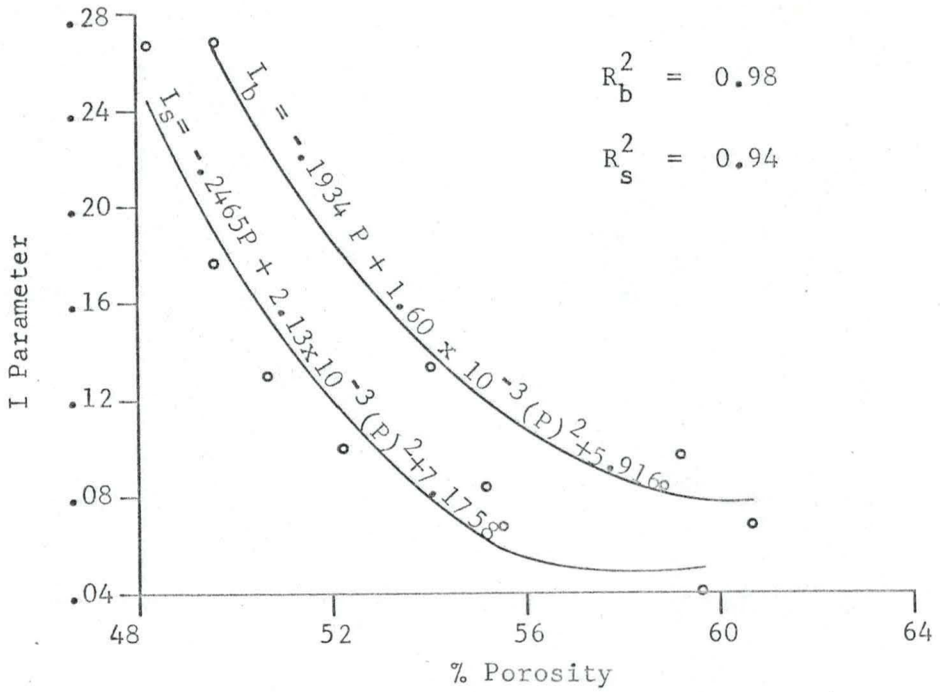

Figure 20. Curve linear relationship of I parameter to porosity.

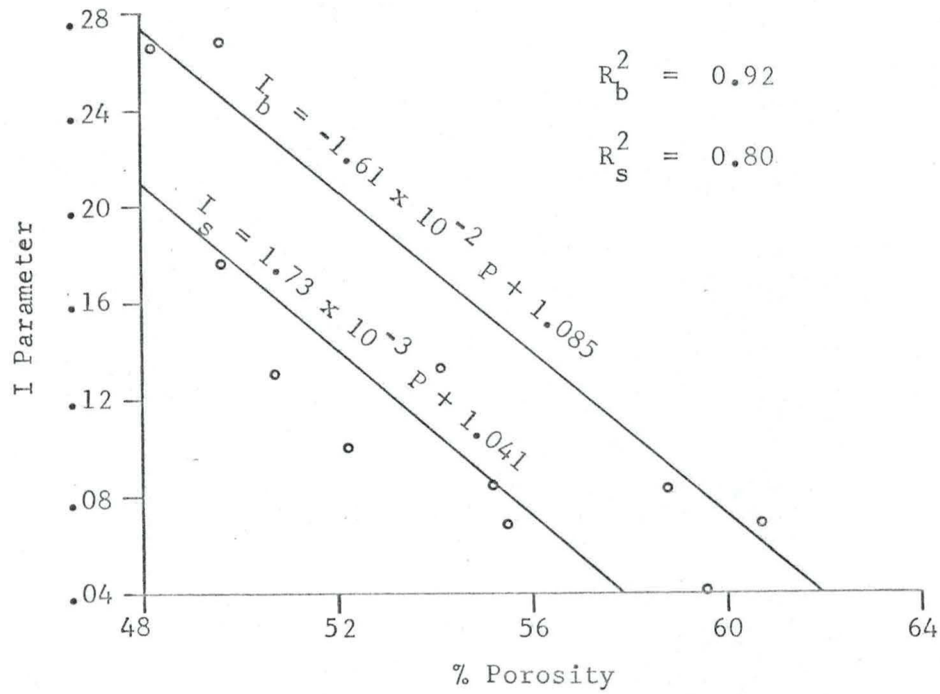

Figure 21. Linear relationship of I parameter to porosity.

The Darcy equation (1) states that the function v(i) has a slope K, which is the conductivity of the soil, and an intercept of zero. A linear equation of the form

$$Y = b_o + b_1 X_1$$

was fitted to the data from all runs (Table 3). In equation (9), Y is equivalent to v and b_1 is equivalent to K. If the data obeyed equation (1), then the intercept b_o should not differ from zero. The parameter differed significantly from zero at the 1% level for all runs. Furthermore, the intercept was negative in all cases. Thus, the equation is essentially useless at low gradients despite the high values obtained for the coefficients of determination. There was only one instance in which less than 99% of the variation was accounted for. This occurred in the Springerville subsoil material which had a porosity of 59.6%.

The linear equation was not applicable to the results of this study. Although Swartzendruber's (1962a) equation (5) better described the relationships found, it did not fit all runs equally well (see Figures 8, 9, and 11). An empirical equation written as

$$v = Ci^B \tag{12}$$

was fitted to the flow data by regression analysis after readjustment to the form

$$\ln v = \ln C + B \ln i . \tag{13}$$

Table 3. Coefficients for $Y = b_o + b_1X_1$ model.

BD	% Porosity	Regression Coefficients b_o	b_1	Partial Correlation Coefficients Y vs X	Coefficients of Determination R^2
		Springerville Soil			
1.10	59.6	-.06858	.02159	.9898	.9797
1.21	55.5	-.004957	.001783	.9996	.9992
1.22	55.2	-.007383	.02292	.9998	.9996
1.30	52.2	-.005118	.02232	.9996	.9992
1.34	50.7	-.001460	.009023	.9974	.9947
1.37	49.6	-.003605	.006403	.9997	.9993
1.41	48.2	-.002197	.002167	.9988	.9976
		Brolliar Soil			
1.07	60.7	-.04165	.2337	.9961	.9922
1.12	58.8	-.01616	.07480	.9982	.9963
1.25	54.1	-.006384	.02518	.9995	.9989
1.37	49.6	-.004728	.006968	.9985	.9970

The equation is reminiscent of the Darcy equation (1) where C is analogous to K. It was thought that flow might be proportional to some power (B) of the hydraulic gradient and that the B parameter would therefore index non-Darcy behavior. Although the equation appeared suitable at lower porosities, it deviated considerably at the higher porosities where the flow relationship became more linear (Table 4).

Non-Darcy behavior was further investigated using a quadratic function fitted to the curve-linear regression equation of

$$\ln Y = b_o + b_1 \ln X_1 + b_2(\ln X_1)^2 \qquad (14)$$

where Y is the flow and X_1 is the hydraulic gradient. The parameters for the equation together with the partial correlation coefficients and coefficients of determination (R^2) for all soils are given in Table 5. Equation (14) fit the data extremely well. There were only two cases in which less than 99% of the variation in flow could be accounted for. This occurred at the higher porosities where most of the variation was encountered.

Although the equation does not hold at the origin, it shows that zero is rapidly approached at hydraulic gradients in the domain of 0-1 cm of mercury. The low gradients in this domain of the function are exactly those that exist most often in the Beaver Creek area. However, the equation clearly shows, by virtue of its close fit to the data over the range of the flow rates observed, the non-linearity of the flow relationship. The relationships differed significantly from a straight line proportional relationship at all but the lowest porosities for

Table 4. Coefficients for $\ln Y = b_o + b_1 \ln X_1$ model.

BD	% Porosity	Regression Coefficients		Partial Correlation Coefficients	Coefficients of Determination
		b_o	b_o	Y vs X	R^2
			Springerville Soil		
1.10	59.6	-1.415	2.3698	.9575	.9168
1.21	55.5	-4.460	1.2133	.9971	.9942
1.22	55.2	-4.239	1.1928	.9965	.9931
1.30	52.2	-4.248	1.2586	.9925	.9851
1.34	50.7	-4.646	.8893	.9825	.9653
1.37	49.6	-5.513	1.1569	.9989	.9978
1.41	48.2	-6.586	1.1235	.9997	.9994
			Brolliar Soil		
1.07	60.7	-1.2497	2.391	.9623	.9260
1.11	59.2	-3.0119	1.7628	.9835	.9674
1.12	58.8	-3.0670	1.6158	.9891	.9782
1.25	54.1	-4.1284	1.2503	.9966	.9932
1.37	49.6	-5.353	1.1115	.9994	.9988

Table 5. Coefficients for $\ln Y = b_o + b_1 \ln X_1 + b_2(\ln X_1)^2$ model.

BD	% Porosity	Regression Coefficients			Partial Correlation Coefficients		Coefficients of Determination
		b_o	b_1	b_2	Y vs X		R^2
				Springerville Soil			
1.10	59.6	-1.405	.8733	-1.1793	.9575	-.9790	.9758
1.21	55.5	-4.3647	1.2944	-.07225	.9971	.6728	.9983
1.22	55.2	-4.208	1.2390	-.02768	.9965	.7569	.9940
1.30	52.2	-4.0816	1.3686	-.1268	.9925	.5799	.9949
1.34	50.7	-4.894	.87217	.09450	.9825	.2761	.9930
1.37	49.6	-5.5538	1.2927	-.04475	.9989	.9344	.9994
1.41	48.2	-6.589	1.1288	.001403	.9997	.9636	.9994
				Brolliar Soil			
1.07	60.7	-1.643	.6888	-.9389	.9623	-.9825	.9721
1.11	59.2	-2.742	1.5144	-.4065	.9835	-.7514	.9968
1.12	58.8	-2.875	1.4396	-.2471	.9891	-.7384	.9942
1.25	54.1	-4.0613	1.2729	-.0453	.9966	.3629	.9949
1.37	49.6	-5.3526	1.1133	-.0006897	.9994	.8994	.9988

both soils. This is illustrated in Figures 22 and 23. Three typical runs for each of the two soils at similar porosities were fitted to equation (14) and plotted on log-log scale. It can be noted in both soils that as porosity decreases or bulk density increases, the departure from non-Darcy flow becomes greater.

The comparison of equations (5), (9), and (14) to the actual data is given in Tables 3-A and 4-A of the Appendix. Equation (9), the linear model represented the worst fit of all the models used. The equation predicts negative flow rates at and below 0.12×10^{-3} and 0.0492×10^{-3} cm/min for the Springerville and Brolliar subsoil materials, respectively. This feature makes the model meaningless at flow rates below these values. Swartzendruber's semi-empirical equation (5) predicts more realistic flow rates at the lower flows than did equation (9). However, the magnitude of departure from the actual flow rates for both soils is large at the lower flows and small at the higher flow rates. The departure was greatest at the higher porosities for each soil. The empirical equation (14) very closely predicted the actual flow rates over the entire range of flows for both soils at all bulk densities. The data point out the inaccuracy of Darcy's equation which can be developed from rational considerations. Thus, it appears that after fitting the data to four rather simple functions a more universal function will have to be developed in order to describe the flow behavior in clay subsoil material at low flow rates and hydraulic gradients.

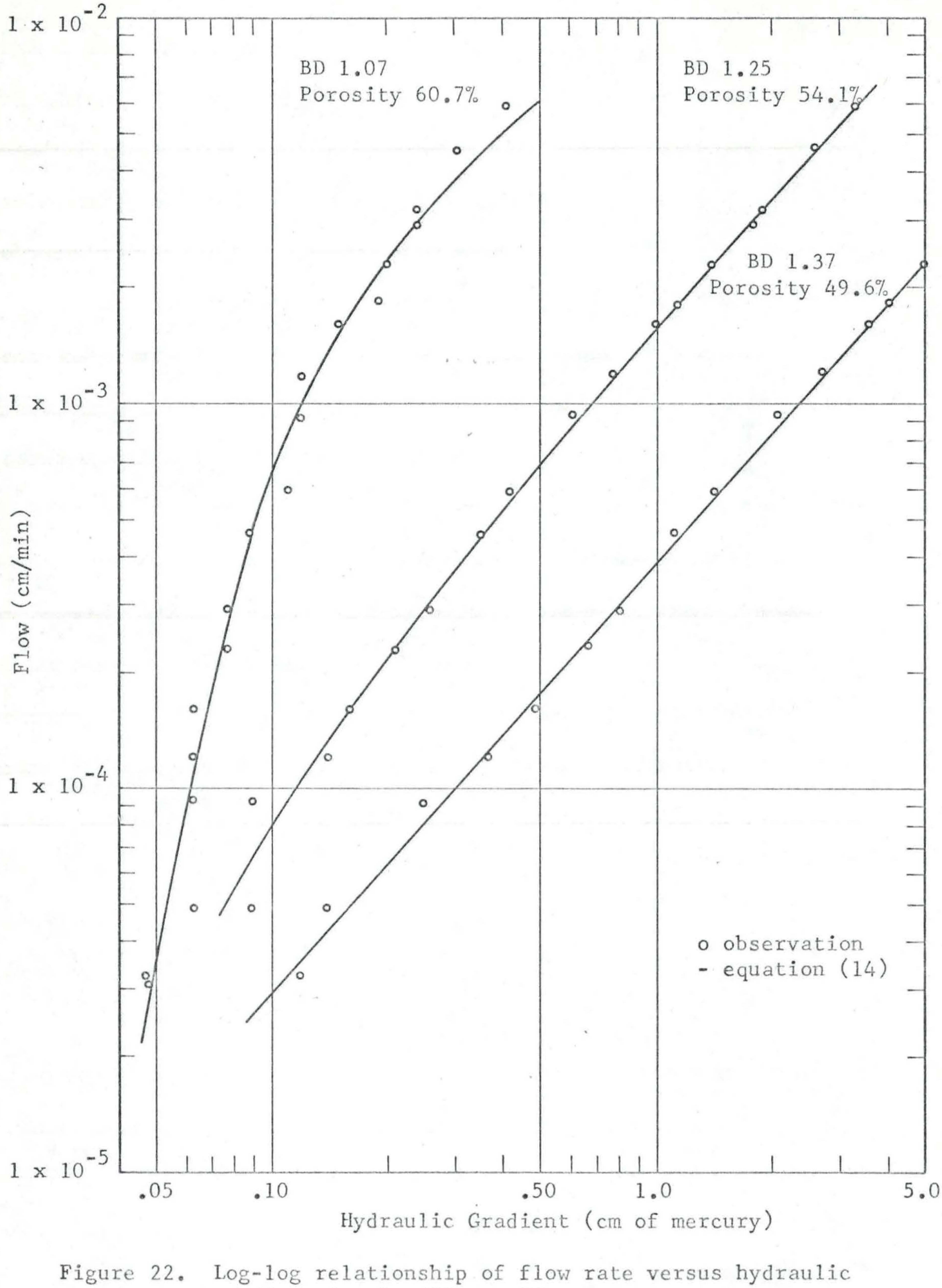

Figure 22. Log-log relationship of flow rate versus hydraulic gradient for Brolliar soil.

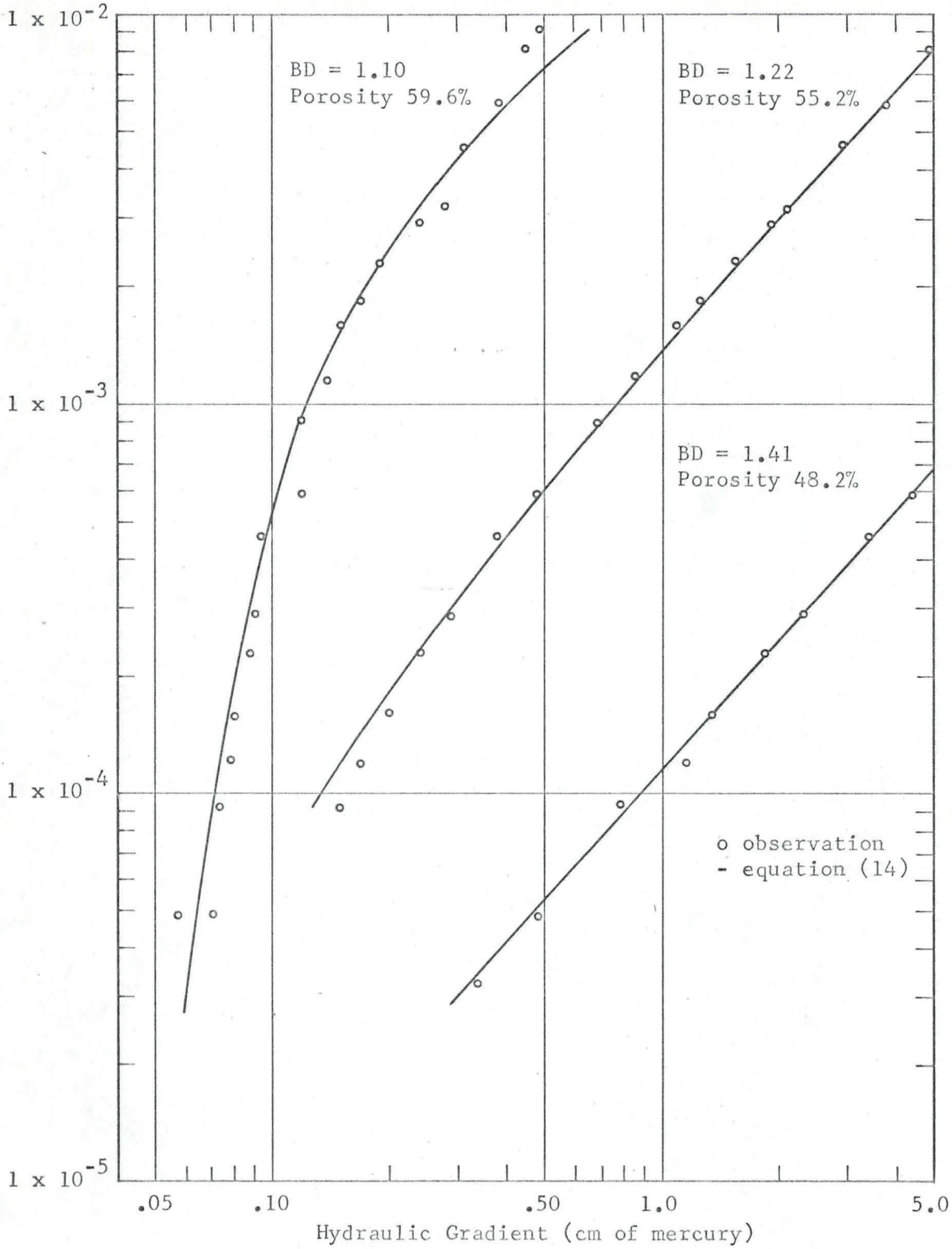

Figure 23. Log-log relationship of flow rate versus hydraulic gradient for Springerville soil.

Swartzendruber (1968) gives an example of the effect of non-Darcy behavior in which surface sealing during raindrop splash is considered. If a threshold gradient, such as discussed by Low (1961), existed with a magnitude of 55 cm of water, then the development of a clay film 0.1 mm thick over the soil surface could support a water depth of 5.4 mm before water movement through the soil could begin. Values for hydraulic gradients in the present study are expressed in cm of mercury per cm length of soil core (Tables 1-A and 2-A of the Appendix) and must be multiplied by 13.6 to be expressed in units of water column height. This would give a threshold value of about 3.68 cm of mercury. Tables 3-A and 4-A show that these values did not occur until high bulk densities and flow rates were obtained. This would indicate that a threshold gradient similar to Swartzendruber's would not be obtained in most instances. Due to this aspect of non-Darcy behavior, flow through the soil of the Beaver Creek area would virtually cease since the soil's surface can be easily sealed by even a slight disturbance.

DISCUSSION

The purpose of the discussion is to review the current theories for describing the hydrologic behavior of clay materials with respect to non-Darcy behavior. All of the theories have merit, but they cannot be completely reconciled with the present state of knowledge. Since they have not been resolved, specific explanations for the hydrologic behavior for the Beaver Creek soils cannot be offered. Since the theories were derived from work on clay soil material, their pertinence to the Beaver Creek area is evident.

Three criteria must be met in a saturated clay sample for Darcy's law to be valid (Olsen 1966). First, the interstitial liquid must exhibit Newtonian behavior. In other words, at every point in the liquid, the viscosity must remain constant with respect to the hydraulic gradients imposed on the sample. Secondly, the clay particles must be arranged in a skeleton sufficiently rigid to prevent seepage forces from modifying the architecture of the pore geometry. Finally, the assumptions for Darcy's law must be met. These assumptions are (1) laminar flow through the porous medium, (2) isotropic permeability, (3) homogeneous porous medium, (4) low hydraulic gradients, and (5) no clay-water interaction.

In order to explain the observed deviations from Darcy's law, several mechanisms have been proposed that provide possible ways in which these criteria can be violated. The mechanisms are quasi-crystalline water, electrokinetic or electroviscous effects, particle

reorientation, and a range in pore sizes. Two of the mechanisms allow for non-Newtonian liquid behavior. One is derived from the postulated existence of a quasi-crystalline structure in the water near clay surfaces. The other mechanism involves the electroviscous component of resistance to liquid movement.

Quasi-Crystalline Theory

Von Englehardt and Tunn (1955), Hansbo (1960), Lutz and Kemper (1959) and Miller and Low (1963) accounted for the non-linearity they observed by invoking the idea that clay surfaces alter water structure. This altered water is thought to be more ordered because of surface-induced hydrogen bonding and is most pronounced at the clay-water interface. The amount of hydrogen-bonded water decreases with distance from the clay surface until normal water is reached. The distance to normal water depends on the surface, its charge, and the exchangable ions present. When low hydrostatic heads are applied, water flows in the center of the pores only where the least altered water exists. With the crystalline structure mechanism at work, presumably a certain yield must be exceeded before the water structure can be deformed and thereafter the rigidity or viscosity of the water structure would decrease with increasing shearing force or gradient (Low 1961). With each higher pressure increment, additional layers of water are sheared, giving increased permeabilities or flow rates. This continues with further increase in head until the whole pore is conducting water. This theory does not provide any information on the behavior of discharge velocity under change of porosity or crystallinity of the clay.

Low (1961) maintains that this theory is not valid at high salt concentrations.

Low suggested that the presence of a threshold gradient would be a critical test for the presence of quasi-crystalline water on clay surfaces. Below the threshold, no water would flow and thus electroviscous or plugging effects could be discounted. Miller and Low (1963) argued that if clay surfaces do order water, then at some clay concentrations this quasi-crystalline water would extend across the entire pore. A finite energy, or head, would be needed to break down this structure barrier before flow would begin. On the basis of the threshold gradient they reported and from experiments which indicated that the activation energy for water flow in clay pastes increased as the applied gradient decreased, Miller and Low concluded that a quasi-crystalline water structure does exist on clay surfaces.

Olsen (1966) observed deviations that are consistent with deviations expected from Darcy's law that postulates a quasi-crystalline structure in the clay pore water.

Miller and Low (1963) investigated the flow of water in clay soils at low hydraulic gradients. The occurrence of deviations in their system is not inconsistent with the absence of deviations in the samples of kaolinite and natural illitic clays of Olsen (1962). Montmorillonite is very fine-grained compared with kaolinite and illite. The influence of quasi-crystalline water could be substantial for flow in the extremely small pores of montmorillonite and negligible for flow in the much larger pores of illite and kaolinite. Thus, according to

Olsen (1966), Miller and Low's data may be interpreted as evidence that there are exceptions to the validity of Darcy's law in very fine-grained natural clays and clay sediments.

Swartzendruber (1962a) presented some conditions within a porous medium which could give rise to the behavior specified by equations (5) and (7). In non-Newtonian flow, the viscosity, taken as a point function, is no longer constant throughout the liquid region, but decreases with the shear rate. This is seen in Figure 4 by taking the slope of the non-Newtonian curve to be the reciprocal of the variable point viscosity.

The reduction in viscosity with shear rate leads consequently to the more-than-proportional increase in the velocity-gradient curve as seen from Figure 5. According to Swartzendruber, it would appear reasonable that in a porous medium the reduction point viscosity with shear rate gives rise to the early, upward-curving aspect of equation (5). If, for increasing gradients, the variable point viscosity is eventually reduced to a uniform and constant value, the linear portion of equation (5) could result. Its slope M could then involve the normal viscosity η and the permeance m as expressed by equation (7).

With the limit of the variable point viscosity presumed to be the normal bulk viscosity, the concept just outlined provides for liquid domains in the porous medium where the point viscosity is higher than the normal bulk viscosity. Such a condition could be accounted for by a water structure as postulated by Low (1961). This would allow for the reduction of the non-Newtonian index I with added

electrolyte since ions usually break down the water's structure. As can be seen from Tables 1 and 2 of the text and Table 5-A (Appendix), the value of I for a given porosity decreased as the salt concentration of the soil increased. This could be expected since for higher concentrations the clay should be less subject to deflocculation and dispersion. This implies that a clay soil with a low sodium content would probably exhibit the greatest degree of non-Newtonian behavior. Adding salt to the soil could cause the flow behavior to be more in the direction of Newtonian flow. The salt concentration had a similar effect on the M parameter. As the salt concentration increased, the value of M decreased. This is to be expected since M is derived in part from the I term of equation (10). There appears to be a general decrease in the M parameter of equation (10) with a decrease in porosity (see Tables 1 and 2). The parameter M could be called the hydraulic transmissibility or hydraulic conductance of the soil.

If the water in the vicinity of clay is quasi-crystalline, the closer the particles are together, the greater the proportion of ordered water. If movement of different layers of this water is shear dependent, the greater the clay concentration, the greater the non-Darcy flow. The Brolliar subsoil material with its 20% clay content would tend to support this, but not the Springerville soil material with its 50% clay content. It is possible that when the clay particles are very close together as in the case of the Springerville material, the force fields are so great that the altered water structure is destroyed and Darcy's flow characteristics appear again.

Electroviscosity Theory

When the cations associated with the negative exchange site on a clay mineral in water are not specifically adsorbed, they distribute themselves in a diffuse layer under the influence of electrostatic and thermal forces. The electrostatic forces of attraction tends to concentrate the cations in the vicinity of the clay particle. Thermal motion or diffusion of these cations creates a tendency for ions to move from the region of higher concentration near the clay mineral surface to regions of low concentration out in solution (Kemper 1960).

When the water moves in thin films on or between negatively charged clay particles, there is an initial tendency for more cations than anions to be carried to the low pressure side of the gradient because of the larger number of cations as compared to free anions in the system. This tendency causes a rapid buildup of positive charge at the low pressure end of the gradient and a decrease in the positive charge at the high pressure end of the gradient. The resulting electrostatic potential gradient exerts a force on the ions in the system, most of which is in turn transmitted to the solution in the immediate vicinity of the ions.

Kemper (1960) determined that the presence of ions associated with a charged clay surface causes a reduction in solution velocity and electroviscous drag decreases with increasing hydraulic gradient. The reduction in velocity was generally more marked as the liquid film became thinner and the ions of the diffuse layer occupied a proportionately greater part of the liquid volume. Under these conditions the hydrated ions exert a large portion of the total drag on the liquid

movement. When the films become very thin the drag on the liquid motion caused by the proximity of the solid surface becomes so large that the drag offered by the ions is a smaller part of the total resistance to flow.

Reduction of the external electrolyte concentration causes the resistance to flow to be greater by allowing the ions associated with the solid surface to extend further out into the central part of the film. Cations in the central part of the film, where the velocity of the solution is greatest, are moved rapidly with the flow, tending to build up large streaming potentials. Since the streaming potential tends to reverse the direction of cation movement, increase the rate of anion movement and there are more cations than anions in the liquid, the net effect of the larger streaming potential is to reduce the velocity of liquid flow (Kemper 1960).

An interesting aspect of the effect of ions associated with the charged surface on the velocity of a fluid is the actual reversal of direction of flow next to the solid surface. If a thin film (<30 Å) were associated in parallel with a thicker film (>150 Å), the liquid flow in the thin film would be against the pressure gradient (Kemper 1960). It is apparent that the flow pattern of liquid in media with extensive diffuse layers of associated ions may be very complicated.

Kemper (1960) determined that when the liquid film is not uniform and constrictions exist in the flow channel, his equation for determining average solution velocity in the thin film is probably not valid for systems with low permeability and extensive diffuse layers of

associated ions. Large pressure gradients will not only cause the flow through the constriction to be proportionately greater, but the more rapid flow will sweep hydrated ions associated with the clay particle out of the constrictions and actually increase the intrinsic permeability. Lutz and Kemper (1959) found that increased pressure gradients cause increases in the intrinsic permeability in systems where the diffuse double layers would be expected to extend to an appreciable distance into the flow channels.

A gradient-dependent electroviscous effect might possibly account for equation (5). It would seem necessary, however, to restrict this to water and relatively dilute electrolyte solutions because in concentrated solutions the effect is usually negligible (Swartzendruber 1962a).

Micheals and Lin (1954) postulated an electroviscous resistance to flow which decreased with increasing head as the flow restricting cations were swept into the larger pores. They concluded that these effects were probably small or of no major importance since electrokinetic theory and experimental results suggest that there is a linear relationship between the electroviscous effect and applied pressure.

Particle Reorientation

Two mechanisms provide ways in which seepage forces can cause irreversible changes in the pore geometry. First, seepage forces can consolidate a clay sample so that the pores are irreversibly diminished in size (Lutz and Kemper 1959). Secondly, if some of the finer clay particles exist free within the pores of the load-carrying skeleton of

clay and coarser particles, seepage forces may cause these mobile particles to plug or unplug flow channels in the load-carrying skeleton (Martin 1962).

It has been proposed that reversible pore geometry changes may result from reversible or elastic particle reorientations caused by seepage forces. The pore geometry might be altered in two ways. The seepage forces might realign particles along stream-lines and thereby reduce the tortuosity of the flow paths (Miller and Low 1963). The seepage forces might also reorient particles in such a way that the size distribution of the flow channels is altered (Terzaghi 1925). Reversible particle reorientations would occur with increasing gradients in such a manner that the effective cross section for flow is increased. Some of the larger channels might be enlarged at the expense of the smaller channels. However, essential reversibility of reorientations is required since the careful replications of Von Englehardt and Tunn (1955) rule out the likelihood of irreversible particle reorientations or movements. Von Englehardt and Tunn (1955) reported no data unless the initial results of the flow experiment could be duplicated at the end of the experiment. The reversible reorientations herein considered are analogous to the behavior of the water flow system made up of very expansible rubber tubes as described by Terzaghi (1925).

Micheals and Lin (1954), Martin (1962), and Mitchell and Younger (1967) suggest that particle reorientation is the most important effect in non-Darcy flow. These matrix effects need not be just a simple

movement of particles, but may include bending and the flexing of particles or the breaking of edge-to-surface bonds to permit particle orientation with the flow path.

Lutz and Kemper (1959) and Von Englehardt and Tunn (1955) data may be interpreted as evidence that deviations from Darcy's law can occur in systems that consist partially or entirely of unconfined clays, owing to alterations in the clay fabric in response to large seepage forces. These data raise the possibility that similar deviations may occur under natural occurring gradients in shallow unconfined clays and also in granular sediments containing small amounts of clay.

A certain orientation of the grains in the clay skeleton of the subsoil will be caused by the pressure of the top soil. The results of the consolidometer tests of Hansbo (1960) suggest that the pore water was allowed to escape in a horizontal direction (i.e., parallel to the clay strata) and the coefficient of consolidation was greater than in the case where the pore water was allowed to escape in the vertical direction.

In a saturated soil, the space between the mineral grains is assumed to be filled with pore water, consisting of ions and water molecules, which are more or less rigidly bound to the mineral surface. The pore water seems to be fixed in a rigid lattice and may be regarded as part of the mineral phase. For the water phase, the viscosity was shown by Hansbo (1960) to increase considerably when approaching the mineral surface, from 24 centipoises at 30% to 153 centipoises at 10% water content for the clay in question.

When sedimented clay is gradually loaded by overlying sediments, not all grains appear to become part of the load-carrying network (the rigid phase or clay skeleton). Consequently, within this network, the space may be filled not only with pore water in its present sense but also with mobile particles of colloidal or greater size which may be bound by sorption and hydrodynamical forces (the mobile phase). Hansbo (1960) suggested this last statement as one explanation for the phenomenon observed in his permeability tests. During his tests, the direction of flow through the specimen was often altered. His system behaved as if the mobile particles were being meshed during their travel through the pore space, thus clogging part of the pores. The pores would be re-opened by an increase in flow velocity or by a change in flow direction, or in some cases, after some lapse of time.

From results obtained by Hansbo (1960) it was found that Darcy's law of permeability is not always valid for small pore pressure gradients. The forces which bind the mobile phase gradually become stronger when the distance to the rigid phase decreases. It was also suggested that within certain limits, the clay becomes increasingly porous or more permeable with increasing pore pressure gradient. This deviation from Darcy's law of permeability ought to depend on the interaction between skeleton grains and pore water. With this in mind, Hansbo (1960) studied the results obtained by pH-metric titration of the samples used in his permeability tests. The titer curves showed considerable reactions between the clay and hydrochloric acid for all

of the samples deviating from Darcy's law of permeability. Little reaction between the clay and acid was obtained on samples which were found to obey Darcy's law.

Because of its characteristics, montmorillonite would be expected to be more subject to matrix rearrangements. It would have a large component of particles that can bend, flex, and move, whereas the other kinds of clays do not have as many small particles to move or shift. Because of their low surface area, the clay minerals of kaolinite and illite are usually thought of as minimizing water structure, if they do in fact alter water structure. Montmorillonite, having both a large surface area and associated exchange capacity because it is an expanding mineral, would be expected to maximize any water effect that is a result of surface, exchangable cations or charge-induced phenomena.

It would be expected that if non-Darcy behavior is a result of either water or matrix effects, the subsoil material with the high clay content would have large values of I since this is a measure of non-Darcy behavior. Tables 1 and 2 of the text and Table 5-A of the Appendix indicate that for a given porosity the Springerville soil material with the high clay content produces lower values of I than does the Brolliar material with the lower clay content.

One explanation for this interesting feature is the effects of high clay concentrations on the subsoil material. As the montmorillonite becomes more concentrated in the soil material, the particles are in closer proximity and the swelling pressure between the particles

increases. At some clay concentration, apparently above 20%, these forces could become great enough to stabilize the particle, preventing or reducing matrix effects at the low flow rates used. At the clay concentration of 50%, no particle rearrangement took place or it was so slow that more Darcy flow resulted as is shown in Tables 1 and 2.

Although no evidence indicating a pressure dependent relaxation of the containing cells was found, this possibility cannot be ruled out. In the Brolliar soil material with its low clay content, the permeability and swelling pressures may be such that small changes in cell volume could occur and cause non-linear pressure dissipation. The swelling pressure in the Springerville soil material could be large enough to eliminate cell volume changes.

Range in Pore Sizes

Miller and Low (1963) suggested that non-linear flow could be caused by a range in pore sizes. As the hydraulic gradient was increased, the threshold gradient was exceeded in smaller pores increasing the flow rate. A threshold gradient is necessary for this explanation.

Various authors (Hansbo 1960, Kemper 1960, Olsen 1966) have shown that most of the data explain the two dominant characteristics of the deviations from Darcy's law, namely, the more-than-proportional increase in flow velocity with increasing gradient and the increasing departures from direct proportionality with decreasing electrolyte concentrations in the permeant liquid. Some features of the data are inconsistent with electroviscous drag and irreversible pore geometry

changes as dominant mechanisms (Low 1961). The most likely causes of non-Darcy flow behavior appear to be the quasi-crystalline structure of water near clay surfaces and reversible clay fabric changes induced by seepage forces (Olsen 1966).

Two characteristics of saturated clay systems should govern the extent to which these mechanisms can cause deviations from Darcy's law. They are the sizes of the flow channels and the rigidity of the clay fabric. The influence of the quasi-crystalline structure in clay pore water should increase with decreasing clay pore sizes because, presumably, the rigidity of the water structure decreases with distance from clay surfaces. The clay's fabric susceptibility to alteration by seepage forces should decrease with increasing degrees of consolidation and confinement.

If the water in a porous medium can be modified by the influence of particle surfaces, the classical non-Newtonian or Bingham concepts must be applied with caution. For material flowing in a cylindrical capillary pore, the shear stress is zero at the axis of the pore and maximal at the wall (Reiner 1960). This means that any non-Newtonian effect, be it an elevated shear-rate dependent viscosity or a yield-value Bingham plasticity, will be broken down first at the wall and will persist longest in the central axial portion of the pore. Neither of these effects, however, appears directly comparable with surface-induced changes in water properties, for it would seem that these should be minimal at the center of a pore and maximal at the walls. The approach of Powell and Eyring (1944), involving two types

of bonds, might lead to further explanation of the water properties.

Von Englehardt and Tunn (1955) also recognized an alternative mechanism consisting of adsorbed, immobile water layers on the particle surfaces with Newtonian conditions prevailing elsewhere. Increased shear stress would need to decrease the thickness of the immobile water layers so that the effective cross-section for flow would increase with the gradient.

SUMMARY

The present study has been concerned entirely with liquid-saturated porous media. The same non-Newtonian effects, perhaps to an even greater degree, might well be expected in partially saturated porous media, since liquid movement must then take place in closer proximity to the particle surfaces. Because of the relationship of saturated water flow to soil drainage, the present study has clear relevance in watershed management for conditions of excess precipitation. Also, if non-Newtonian flow manifests itself in partially saturated soils, then further important implications arise on the question of unsaturated flow to the evapotranspiration stream. Problems introduced by unsaturated drainage as a source of base flow also become pertinent.

If existing greater-than-proportional behavior were ignored when determining hydraulic conductivity by a laboratory test, Figures 8 through 19 illustrate the resulting implications. If the test were conducted at a high gradient and the flow condition of interest occurred at a low gradient, the effective value of K under the flow condition of interest would be overestimated. The reverse would be true if the gradient were less than the gradient at the flow condition of interest. The magnitude of discrepancy would depend on the velocity-gradient relationship and on the spread between the test gradient and the gradient under the flow condition of interest.

APPENDIX

STATISTICAL DATA

Table 1-A. Actual flow rates and hydraulic gradients for the Brolliar subsoil material.

Actual Flow (10^{-3} cm/min)	Hydraulic Gradient (cm mercury) BD 1.07 Porosity 60.7%	1.11 59.2%	1.12 58.8%	1.25 54.1%	1.37 49.6%
.0325	.047	.063	.047	.047	.12
.0492	.063	.067	.063	.09	.14
.0927	.063	.087	.083	.09	.25
.12	.063	.093	.083	.14	.37
.16	.063	.10	.087	.16	.49
.23	.077	.12	.11	.21	.67
.294	.077	.14	.14	.26	.81
.456	.087	.16	.17	.35	1.13
.590	.11	.19	.20	.42	1.44
.913	.12	.24	.24	.61	2.10
1.18	.12	.28	.30	.79	2.74
1.60	.15	.35	.38	1.00	3.60
1.83	.19	.40	.44	1.12	4.06
2.3	.20	.48	.52	1.39	5.13
2.9	.24	.60	.66	1.77	6.52
3.2	.24	.63	.68	1.87	6.80
4.56	.31	.84	.90	2.58	9.20
5.9	.41	1.07	1.14	3.32	11.66

Table 2-A. Actual flow rates and hydraulic gradients for the Springerville subsoil material.

Actual Flow (10^{-3} cm/min)	Hydraulic Gradient (cm mercury)						
	BD 1.10 Porosity 59.6%	1.21 55.5%	1.22 55.2%	1.30 52.2%	1.34 50.7%	1.37 49.6%	1.41 48.2%
.0325		.077		.077	.027		.33
.0492	.07	.087	.057	.093	.035	.20	.48
.0927	.073	.13	.15	.12	.19	.34	.79
.12	.077	.17	.17	.13	.25	.44	1.15
.16	.08	.20	.20	.16	.32	.52	1.37
.23	.087	.27	.24	.22	.44	.69	1.88
.294	.09	.31	.29	.26	.55	.83	2.31
.456	.093	.45	.38	.35	.76	1.18	3.40
.590	.12	.57	.48	.46	1.03	1.43	4.39
.913	.12	.83	.67	.65	1.77	2.19	6.38
1.18	.14	1.08	.86	.83	1.87	2.85	8.27
1.60	.15	1.38	1.09	1.09	2.42	3.81	10.66
1.83	.17	1.57	1.26	1.25	2.79	4.24	11.76
2.3	.19	1.94	1.53	1.58	3.56	5.25	
2.9	.24	2.46	1.94	1.96	4.65	6.75	
3.2	.28	2.63	2.11	2.14		7.21	
4.56	.31	3.62	2.91	2.87		9.98	
5.9	.38	4.65	3.78	3.73			
8.1	.45		4.94				
9.13	.49		5.60				
12.0			7.56				

Table 3-A. Actual and predicted flow using the Swartzendruber, linear and log-log model on the Brolliar soil material.

Actual Flow	Porosity 60.7%			Porosity 59.2%			Porosity 58.8%		
(10^{-3} cm/min)	Eq. (5)	Eq. (9)	Eq. (14)	Eq. (5)	Eq. (9)	Eq. (14)	Eq. (5)	Eq. (9)	Eq. (14)
.0325	.242	-.213	.0315	.106	-.0824	.0406	.061	-.136	.0306
.0492	.406	.0661	.110	.119	-.0628	.0456	.105	-.0464	.0624
.0927	.406	.0661	.110	.189	.0547	.0956	.171	.0608	.114
.12	.406	.0661	.110	.212	.0939	.116	.171	.0608	.114
.16	.406	.0661	.110	.24	.1331	.138	.185	.0787	.124
.23	.470	.289	.221	.327	.270	.229	.275	.204	.202
.294	.470	.289	.221	.422	.348	.289	.405	.365	.320
.456	.70	.457	.33	.522	.505	.428	.547	.526	.456
.590	1.02	.848	.679	.683	.642	.557	.647	.686	.606
.913	1.17	1.071	.92	.967	.956	.896	.905	.883	.800
1.18	1.17	1.071	.92	1.2	1.21	1.19	1.23	1.22	1.15
1.60	1.65	1.574	1.54	1.6	1.60	1.66	1.7	1.65	1.63
1.83	2.3	2.13	2.26	1.95	1.90	2.00	2.0	1.99	1.99
2.3	2.5	2.36	2.56	2.4	2.37	2.53	2.5	2.4	2.46
2.9	3.2	3.08	3.39	3.2	3.05	3.25	3.23	3.1	3.2
3.2	3.2	3.08	3.39	3.4	3.23	3.39	3.3	3.24	3.3
4.56	4.46	4.31	4.44	4.75	4.48	4.35	4.58	4.46	4.42
5.9	6.3	5.93	5.14	6.2	5.85	5.18	5.9	5.7	5.47
8.1									
9.13									
12.0									

Table 3-A.--Continued

Actual Flow (10^{-3} cm/min)	Porosity 54.1%			Porosity 49.6%		
	Eq. (5)	Eq. (9)	Eq. (14)	Eq. (5)	Eq. (9)	Eq. (14)
.0325	.0148	-.0683	.0282	.0117	-.0530	.0363
.0492	.0464	.00991	.0719	.0158	-.0414	.0442
.0927	.0464	.0159	.0757	.0437	.0135	.0834
.12	.1	.1002	.132	.0851	.0702	.126
.16	.13	.142	.162	.132	.133	.175
.23	.20	.232	.231	.212	.220	.25
.294	.277	.311	.294	.278	.292	.30
.456	.43	.479	.437	.433	.450	.454
.590	.56	.612	.557	.587	.605	.576
.912	.909	.955	.879	.916	.938	.877
1.18	1.25	1.28	1.2	1.24	1.25	1.18
1.6	1.65	1.65	1.57	1.66	1.68	1.6
1.83	1.88	1.88	1.81	1.90	1.91	1.82
2.3	2.4	2.4	2.30	2.43	2.45	2.36
2.9	3.1	3.0	3.0	3.13	3.14	3.08
3.2	3.3	3.2	3.22	3.3	3.28	3.22
4.56	4.65	4.50	4.61	4.47	4.48	4.52
5.9	6.0	5.8	6.0	5.7	5.71	5.8
8.1						
9.13						
12.0						

Table 4-A. Actual and predicted flow using the Swartzendruber, linear and log-log model on the Springerville soil material.

Actual Flow (10^{-3} cm/min)	Porosity 59.6%			Porosity 55.5%			Porosity 55.2%		
	Eq. (5)	Eq. (9)	Eq. (14)	Eq. (5)	Eq. (9)	Eq. (14)	Eq. (5)	Eq. (9)	Eq. (14)
.0325				.0390	-.0204	.0387			
.0492	.569	-.175	.0848	.0478	-.0076	.0456	.0251	-.0833	.0363
.0927	.608	-.106	.1046	.0908	.0435	.0812	.129	.070	.130
.12	.66	-.0361	.127	.14	.103	.131	.16	.0974	.146
.16	.699	.0335	.153	.17	.137	.154	.20	.152	.187
.23	.793	.173	.213	.25	.227	.230	.26	.212	.238
.294	.835	.242	.248	.304	.278	.277	.335	.300	.299
.456	.876	.312	.287	.479	.457	.444	.476	.448	.418
.590	1.26	.80	.64	.63	.614	.60	.636	.607	.552
.913	1.26	.87	.70	.954	.943	.932	.939	.919	.83
1.18	1.56	1.22	1.05	1.27	1.26	1.26	1.24	1.23	1.11
1.6	1.71	1.57	1.46	1.6	1.64	1.65	1.6	1.61	1.48
1.83	2.01	1.84	1.82	1.88	1.89	1.90	1.88	1.89	1.75
2.3	2.31	2.26	2.38	2.3	2.36	2.38	2.3	2.34	2.21
2.9	3.1	3.31	3.78	3.0	3.03	3.03	3.0	3.0	2.89
3.2	3.7	4.21	4.85	3.2	3.24	3.25	3.2	3.28	3.18
4.56	4.16	4.84	5.47	4.44	4.51	4.42	4.5	4.6	4.59
5.9	5.2	6.30	6.45	5.7	5.83	5.59	5.9	6.0	6.12
8.1	6.3	7.7	6.83				7.8	7.95	8.22
9.13	6.9	8.39	6.88				8.83	9.02	9.39
12.0							12.0	12.25	13.0

Table 4-A.--Continued

Actual Flow (10^{-3} cm/min)	Porosity 52.2%			Porosity 50.7%		
	Eq. (5)	Eq. (9)	Eq. (14)	Eq. (5)	Eq. (9)	Eq. (14)
.0325	.0382	.00038	.0411	.00158	-.0176	.0361
.0492	.0531	.0270	.0576	.00289	-.0133	.040
.0927	.0822	.0644	.0834	.0622	.0858	.111
.12	.0938	.0804	.0953	.096	.125	.139
.16	.132	.139	.142	.14	.172	.173
.23	.22	.224	.219	.22	.247	.228
.294	.274	.294	.284	.291	.319	.282
.456	.415	.438	.432	.435	.459	.394
.590	.590	.619	.624	.62	.631	.540
.913	.902	.912	.946	1.1	1.11	.999
1.18	1.20	1.21	1.27	1.2	1.11	1.06
1.6	1.6	1.62	1.71	1.58	1.53	1.46
1.83	1.89	1.87	1.97	1.84	1.77	1.75
2.3	2.4	2.40	2.51	2.37	2.27	2.41
2.9	3.0	3.0	3.06	3.1	2.98	3.44
3.2	3.3	3.3	3.3			
4.56	4.54	4.47	4.52			
5.9	6.0	5.85	5.26			
8.1						
9.13						
12.0						

Table 4-A.--Continued

Actual Flow (10^{-3} cm/min)	Porosity 49.6%			Porosity 48.2%		
	Eq. (5)	Eq. (9)	Eq. (14)	Eq. (5)	Eq. (9)	Eq. (14)
.0325				.0211	-.0007	.033
.0492	.0369	.0057	.0473	.0385	.0216	.049
.0927	.0872	.0684	.0937	.080	.0702	.087
.12	.13	.117	.133	.13	.126	.132
.16	.16	.152	.163	.16	.16	.16
.23	.24	.232	.23	.24	.24	.23
.294	.30	.296	.292	.306	.306	.289
.456	.461	.454	.44	.470	.473	.449
.590	.576	.57	.55	.618	.629	.597
.913	.926	.92	.90	.917	.938	.91
1.18	1.23	1.23	1.21	1.2	1.23	1.22
1.6	1.7	1.66	1.66	1.6	1.6	1.62
1.83	1.87	1.86	1.86	1.72	1.77	1.80
2.3	2.3	2.32	2.3			
2.9	3.0	3.01	3.0			
3.2	3.2	3.22	3.22			
4.56	4.51	4.5	4.47			
5.9						
8.1						
9.13						
12.0						

Table 5-A. Physical and chemical properties of subsoil material.

	pH	Na	Sol. Salts		NO_3
	Paste	meq/l	$EC_e \times 10^3$	ppm	ppm
Springerville	7.4	2.1	.60	420	8
Brolliar	5.4	.78	.40	280	10

	PO_3	CEC	N	Ca	Mg
	ppm	meq/100 g	KJELDAHL %	meq/l	Sat. Ext.
Springerville	.5	41.2	.26	2.1	.8
Brolliar	5.0	60.0	.35	2.3	1.7

	Sand	Silt	Clay	O.M.
	%	%	%	%
Springerville	9	41	50	1.47
Brolliar	30	50	20	5.39

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SECTION 8

THE VOLUME-WATER CONTENT RELATIONSHIP
OF TWO BEAVER CREEK SOILS

by

Herbert S. Garn

PROBLEM

Little is known about the Beaver Creek soils and their water relationships. A quantitative investigation of the shrinking of two montmorillonitic soils, Brolliar and Springerville, with water content would be helpful in understanding the water-holding and sealing properties of these soils. A quantitative knowledge of the amount of shrinkage over a range in water content of the soil with a known percent montmorillonite composition would be helpful also, since some soil properties change with a change in soil volume.

OBJECTIVES

Determine changes in volume of the two soils concurrently with changes in water content as the soil dries. Attempts will be made to explain differences in the water content-volume relationship between the two soils by the percent montmorillonite composition of each soil.

METHODS

Water Content and Volume Measurements

Soil samples were ground up and sieved through a 1 mm. screen; this fraction was then mixed with water to form a thick, pasty slurry of uniform moisture content. Equal amounts (approximately 30 ml.) of this slurry were then placed in brass rings having a glass bottom. The bottoms and sides of these rings were greased to assure free shrinkage. The soil samples were then allowed to air dry slowly.

During the drying period the soil samples were weighed for changes in water content and were measured for corresponding changes in volume. The final measurement was on the oven-dry sample, taken as zero water content.

Volume was measured by placing a cone over the brass ring containing the soil sample and noting the volume of mercury required to fill the ring and cone.

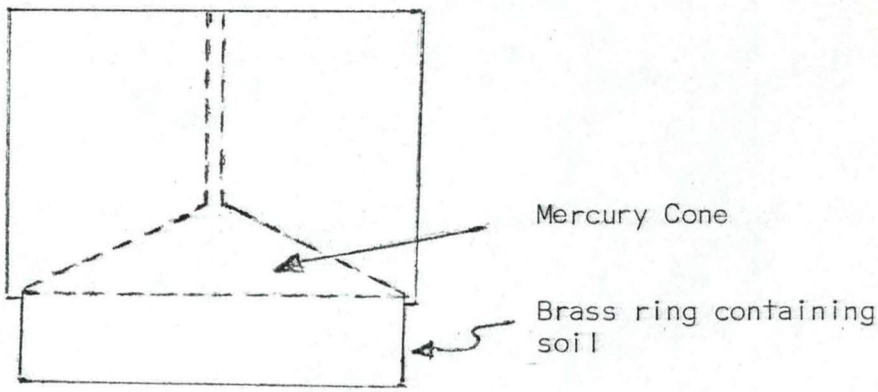

Figure 1. Volume measuring device.

Quantitative Determination of Montmorillonite

A method for determining percent montmorillonite composition of a soil has been developed by Alexiades and Jackson (Alexiades and Jackson, 1965). After a soil sample has been made organic-matter-free, calcium-carbonate-free, and iron-oxide-free, it is dispersed, fractionated, and prepared for cation-exchange capacity determination as outlined in the above publication. The equation for the montmorillonite composition is:

$$\% \text{ montmorillonite} = \frac{\text{CE } (K//NH_4) - (5 + 105 \text{ Amor})}{105} \times 100$$

where CEC ($K//NH_4$) is the determined potassium of the soil extract expressed in milliequivalents per 100 grams of oven-dry soil, and Amor is the percent of amorphous material having an S_iO_2-Al_2O_3 molar ration of three or above.

Since the Brolliar and Springerville soils have negligible amounts of iron oxide and amorphous material, the procedure has been modified to omit these steps. The equation for the composition of montmorillonite then becomes:

$$\% \text{ montmorillonite} = \frac{CEC(K//NH_4)-5}{105} \times 100$$

Percent montmorillonite composition was determined for two samples from each soil and the result averaged.

RESULTS AND DISCUSSION

The Brolliar and Springerville soils are known, from previous studies, to contain about 32 percent and 49 percent clay, respectively. The Springerville soil contains 1.5 times the amount of clay as the Brolliar. This study agrees with these findings, the Springerville soil having 1.6 times the amount of clay as the Brolliar.

The two soils were found to have similar percent montmorillonite composition, the clay in the Springerville soil consisting of 74.9 percent montmorillonite and that of the Brolliar consisting of 69.6 percent. However, since the Springerville contains 1.6 times the amount of clay as the Brolliar, the Springerville soil actually contains 1.8 times the amount of montmorillonite as the Brolliar soil.

This difference in montmorillonite content of the two soils can be seen in their different reactions of change in soil volume with change in

moisture content (see figures two and three). Both soils had similar initial total volume (solid volume, plus air space volume, plus water volume) and water content, but the relationship in the Springerville soil remained linear down to a much lower water content than in the Brolliar soil. Also, the Springerville soil remained linear down to a much lower water content than in the Brolliar soil. Also, the Springerville soil shrank to less than 50 percent of its initial volume, while the Brolliar shrank to 65 percent of its initial volume.

This change in volume affects certain soil properties and should not be ignored, as is done in present soil analyses. Studies of bulk densities of soils should take into account this volume-water content relationship. A change in volume with water content also has profound effects on the water flow-properties of the soil and possibly also on the water storage capabilities of a soil. Darcy's Law may not apply to montmorillonitic soils if this change in volume is not accounted for.

Considering a soil in the field that is partially confined, free shrinkage or expansion would be hindered, and this change in volume accompanying a change in water content would take place at the expense of its pore space volume. Thus, with an increase in water content, such a soil would seal rapidly, impairing the movement of water and changing its water storage capacity.

That portion of the curve which is a straight line in figure 3 represents the stage where the pore space is filled only with water. Here the volume of water lost is accompanied by an equal decrease in soil volume. A deviation of the curve from linearity indicates the stage where pore space is partially filled with water and partially with air. The difference between

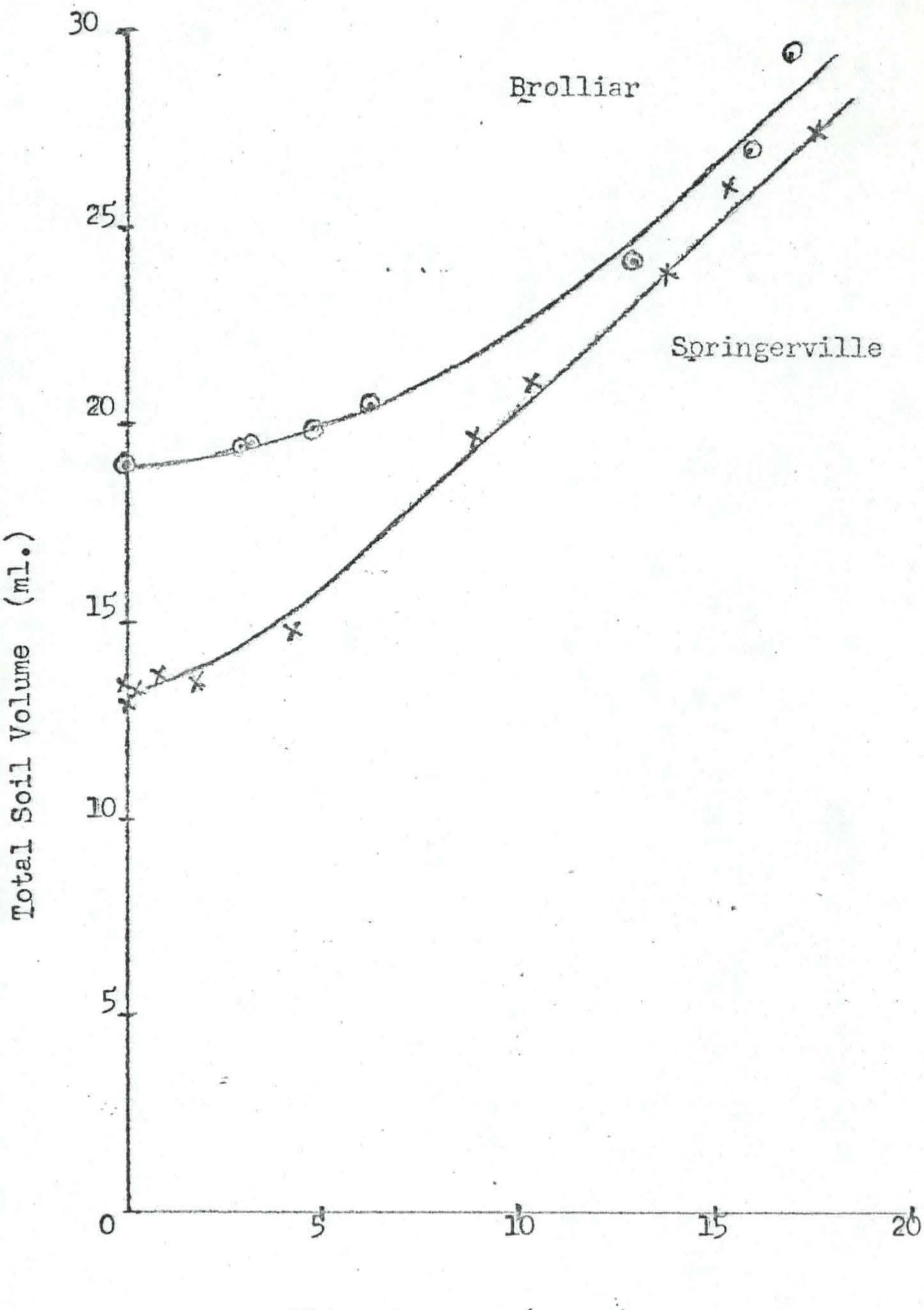

Figure 2.
Soil volume versus water content of two clay soils containing montmorillonite.

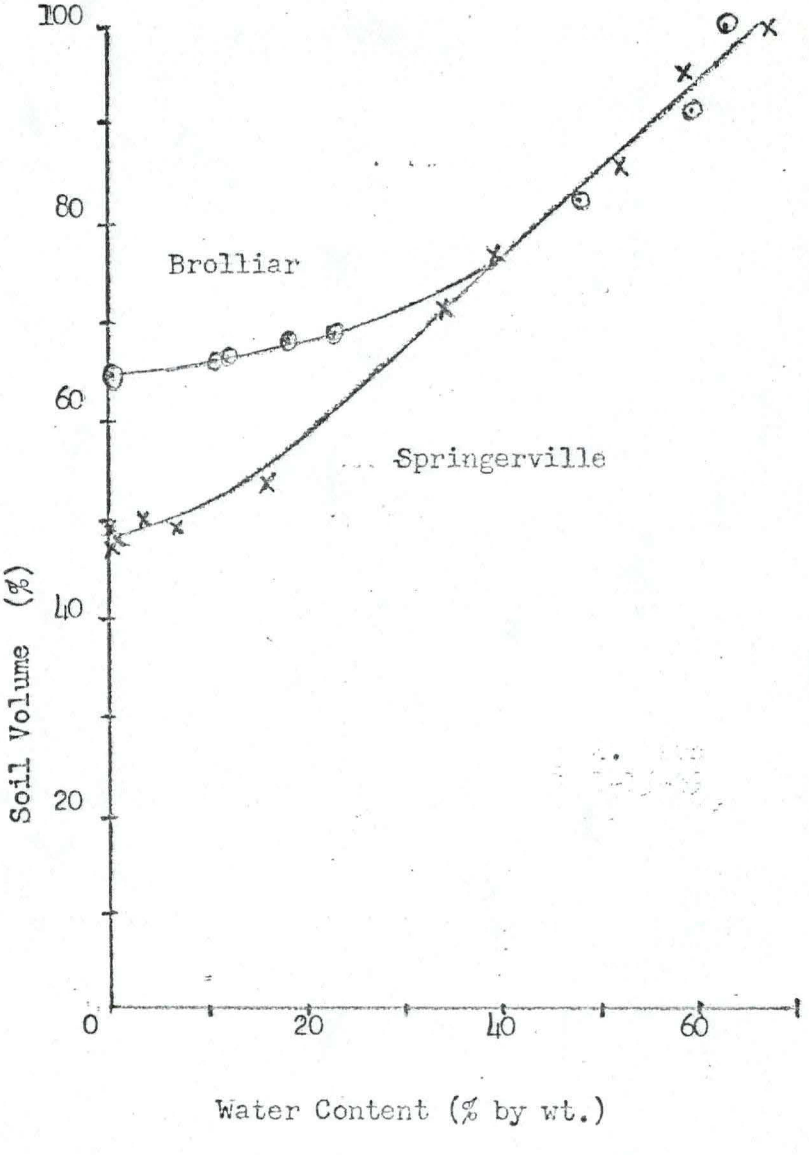

Figure 3.
Soil volume percent of initial volume versus moisture content percent for two clay soils containing montmorillonite.

the curved part of the curves and the extension of the linear part would be the air pores space volume (Wright, 1934). However, the actual case may not be this simple.

A unit cell of montmorillonite has a maximum height of 21.4 $\overset{\circ}{A}$ and a minimum height of 9.6 A^{o}, a change in volume of 55 percent. Since the Brolliar soil has a montmorillonite content of 22 percent, and Springerville a content of 37 percent, the maximum shrinkage of each would only be 12 percent and 20 percent by volume respectively, if shrinkage was due only to loss of water from between the silicon layers of the montmorillonite crystal. However, the actual shrinkage is much beyond these values. What may be happening is that water being lost from pores draws the soil particles together (straight portion of the curve) until water films are very thin and tensions are reached so that at some point water is lost from both pore spaces and between silicon layers of the montmorillonite crystal. This causes a greater change in volume than would be expected from the montmorillonite content alone. Therefore, change in volume is probably a function of total clay content of the soil as well as montmorillonite content.

Further studies investigating this volume-water content relationship would be helpful in clearing up some questions brought forth by this study. What is the relationship between percent montmorillonite and percent clay and the water content-volume curve? More soils of varying total clay and montmorillonite content would have to be investigated, including a standard soil with no montmorillonite content. Does the pore space of a soil change with changing volume? Air pore space could be measured with a pyconmeter in conjunction with volume and water content measurements. Answers to these questions would be helpful in explaining this relationship further and in understanding the processes involved.

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SECTION 9

THE SIZE DISTRIBUTION OF SURFACE ROCKS

ON SEVERAL BEAVER CREEK WATERSHEDS

by

John L. Thames

Large numbers of rocks on the soil surface of a watershed will influence the hydrograph. Surface storage and the path length of overland flow would be increased, infiltration would be influenced in some undetermined manner and the degree of turbulence of overland flow affected.

Because the Beaver Creek soils have large numbers of surface rocks, it was thought worthwhile to develop an analytic description of their distribution for the watersheds sampled. The number and sizes of rocks on the soil surface of the watersheds were estimated by counts made at 6 x 6 inch intersections of a 50 point grid. One grid sample was taken at each pit sampled in the study. The data are given in Table I.

Preliminary plotting indicated rock sizes were not normally distributed but that they could be interpreted in terms of the function F(x) where

F(x) = fraction of rocks on the surface comprised by rocks with a diameter less than x.

A function presented by Best (1945) for rain drop size distribution appeared reasonable. The function is written

$$1 - F = \exp\left[-(x/a)^n\right] \tag{1}$$

where a and n are constants which must be evaluated for a particular watershed. Rearranging equation 1 to clear the negative exponent gives

$$\frac{1}{1-F} = \exp\,(x/a)^n \tag{2}$$

since

$$\log \exp\,(x/a)^n = \ln \exp\,(x/a)^n \log e, \tag{3}$$

then

$$\log \frac{1}{1-F} = .4343\ (x/a)^n \tag{4}$$

taking the log again gives

$$\log \log \frac{1}{1-F} = .4343 + n(\log x - \log a). \tag{5}$$

since

$$\log .4343 = -.36$$

then

$$\log \log \frac{1}{1-F} = -.36 + n(\log x - \log a). \tag{6}$$

Therefore if equation (1) describes the data then $\log \log \frac{1}{1-F}$ plotted against $\log x$ should yield a straight line with slope n. The intercept will be n log a.+.36.

Linear regressions were run on the transformed data to determine the a and n parameters. Results are given in Table 2. Standard errors are low and coefficients of determination high for all watersheds indicating that equation (1) is satisfactory.

The surface rock distributions for each of the five watersheds are shown plotted in the appendix.

It was also thought that the predominant rock size might be of interest. A general expression for the predominant rock size was obtained from

$$\frac{d^2 F(x)}{dx^2} = 0 \tag{7}$$

in the following manner:

If

$$F = 1 - \exp[-(x/a)^n] \tag{8}$$

then

(9)

This expression is also shown plotted in the appendix for each watershed.

Setting the second derivative equal to zero gives

$$\frac{d^2F}{dx^2} = \left(\frac{n}{a^n}\right) D\left[e^{-\left(\frac{x}{a}\right)^n} x^{(n-1)}\right] =$$

$$\frac{n}{a^n}\left[(n-1)\, e^{-\left(\frac{x}{a}\right)^n}\left(x^{(n-2)}\right) + \left(x^{n-1}\right)\left(D\, e^{-\left(\frac{x}{a}\right)^n}\right)\right] =$$

$$\frac{n}{a^n}\left[(n-1)\, e^{-\left(\frac{x}{a}\right)^n} x^{(n-2)} - \frac{x^{n-1}\, e^{-\left(\frac{x}{a}\right)^n}\, n\, x^{(n-1)}}{a^n}\right] =$$

$$e^{-\left(\frac{x}{a}\right)^n}\left[(n-1)\, x^{(n-2)} - \frac{x^{(n-1)}\, n\, x^{(n-1)}}{a^n}\right] =$$

$$x^{(n-2)}\left[n-1 - \frac{n x^n}{a^n}\right] =$$

$$(n-1) - \frac{n x^n}{a^n} = 0 \qquad (9)$$

Solving for x gives

$$x = a \left(\frac{n-1}{n}\right)^{1/n} \qquad (10)$$

Equation (10) may be used with the values for the a and n parameters given in Table 2 to determine the predominant rock size on the five watersheds.

Table 1. Number of Surface Rocks by Size Classes on Beaver Creek Watersheds.

	Size Class[1]																			
Watershed	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
3	65	27	18	10	7	4	1	0	0	5	2	3	0	1	0	1	1	0	0	0
6	25	35	29	21	15	9	3	10	4	4	2	0	0	0	0	0	0	0	0	0
9	22	26	28	20	14	19	6	9	4	7	2	3	0	1	0	1	0	1	0	0
11	51	29	29	30	11	14	2	9	1	6	4	2	1	1	0	1	0	0	1	0

1) 1 = 1" $\leq S <$ 2"

2 = 2" $\leq S <$ 3"

3 = 3" $\leq S <$ 4"

etc.

Table 2. Regression Analysis of Parameters for Surface Rock Distribution Function.

Watershed	Slope (n)	Intercept (.36 + n log a)	r^2	a
3	.7175	-.5790	.978	2.019
6	1.3199	-1.0974	.944	3.619
9	1.1949	-1.1564	.992	4.639
11	1.8016	-1.5232	.998	4.422
12	1.3187	-1.2202	.995	4.491

SECTION 10

A WATERHSED SOIL SAMPLING GUIDE

by

John L. Thames

The management of a watershed requires knowledge of the hydrologic properties of its soils. A soil sampling operation that is planned both with respect to available resources and the precision desired is the most efficient way of obtaining this information. A first requirement of such an operation is an estimate of the optimum number of samples that must be taken.

This note describes a soil sampling guide developed from an intensive sampling study of Watershed 9. Although the guide was developed for local conditions it should be useful to sampling projects on other watersheds of the mogollon rim areas, particularly as a means of obtaining cost estimates for planning purposes.

The guide is a circular slide rule designed to calculate the optimum number of sample points and subsamples required for either maximum precision with fixed costs or for minimum cost with fixed precision (Figure 1). It contains three variables. The two independent variables are variance, expressed as coefficient of variation, and cost. The dependent variable is number of sample points.

The estimated precision was calculated with the equation

$$CV = \frac{S_1^2}{n_1} \quad \frac{S_2^2}{n_1 n_2}^{\;1/2} \quad \overline{X} \qquad (1)$$

where CV is the coefficient of variation, n_1 is the number of sample points and n_2 is the number of subsamples. The mean, $\overline{X}$, and variances of sample points, S_1^2, and of subsamples, S_2^2, were obtained from an analysis of sampling data.

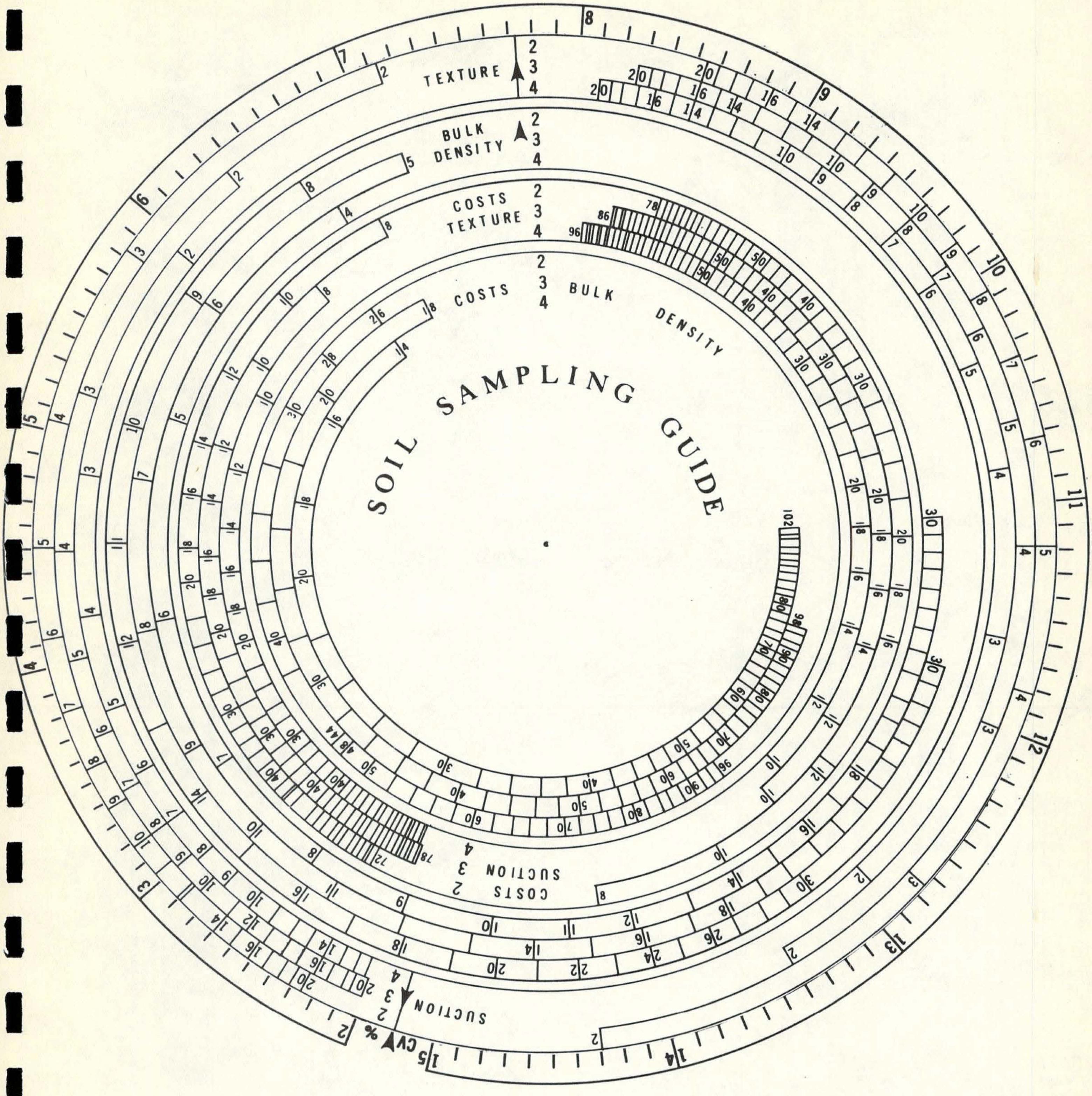


Figure I. -- Watershed Soil Sampling Guide

The optimum number of sample points for fixed cost were calculated with the equation

$$n_1 = \frac{C - C_o}{C_1 + C_2 n_2} \qquad (2)$$

where C is the total cost, C_o an initial cost and C_1 and C_2 are the cost components for samples points and subsamples, respectively.

The costs given on the guide are expressed in man hours for conditions of maximum efficiency. No allowance was made for lost time (Table 1). Sampling was done from pits with a crew of three men, one operating a backhoe and two sampling. Two technicians using streamlined techniques were required for laboratory analyses. In figuring total cost an initial cost of transporting men and equipment to the watershed should be considered. But since this will vary for every situation, it was not included on the guide.

The guide has six fixed scales associated with each soil property to be evaluated. Three of the scales show the number of pits required and three the costs for 2, 3, and 4 subsamples respectively. The precision is read on an outer moveable scale and a moveable index may be added to aid alignment. Three soil properties are included on the guides; soil suction, soil texture and bulk density. These quantities were selected because it was felt that they indexed the hydrologic characteristics of the soils in this study.

The sampling guide provides a conservative estimate. The sampling required to estimate soil texture was determined for the range of particle sizes between .002- and .05-mm, where the highest variances were encountered. Soil suction at 0.33 bars was included on the guide because it was the most variable of five suction values measured over the range 0.05 to 15 bars.

Table I. Cost estimates for the Arizona study.

Sampling	Man Hours	Analysis	Man Hours
Locating points	1.0	Bulk density	.10
Digging pits	.5	Texture	.26
Soil sampling	1.5	Soil suction	.11
Soil preparation	.20		

Over 1200 samples, involving about 10,000 separate analyses, were taken in this study from the profiles of 5 soil series represented on the watersheds. Although the individual watersheds ranged from 104 to 1,121 acres, no consistent pattern was found between variance of the soil properties measured and size of watershed. Variances were also homogeneous between soil series. Thus, it is not surprising that the guide, developed for the surface soil layer of the largest watershed, gave good approximations when tested with data from deeper soil layers and from different watersheds.

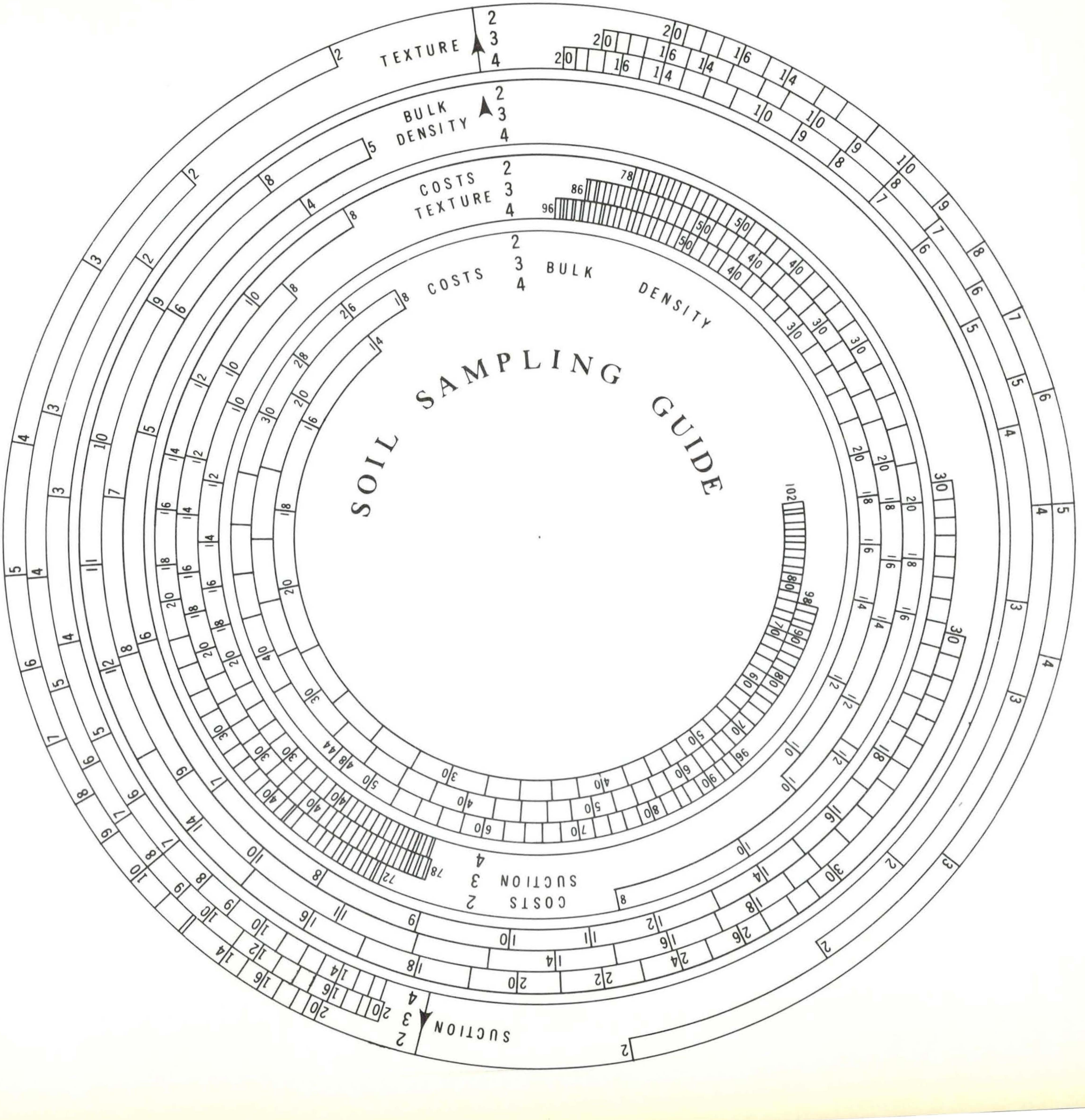
Use of the Guide

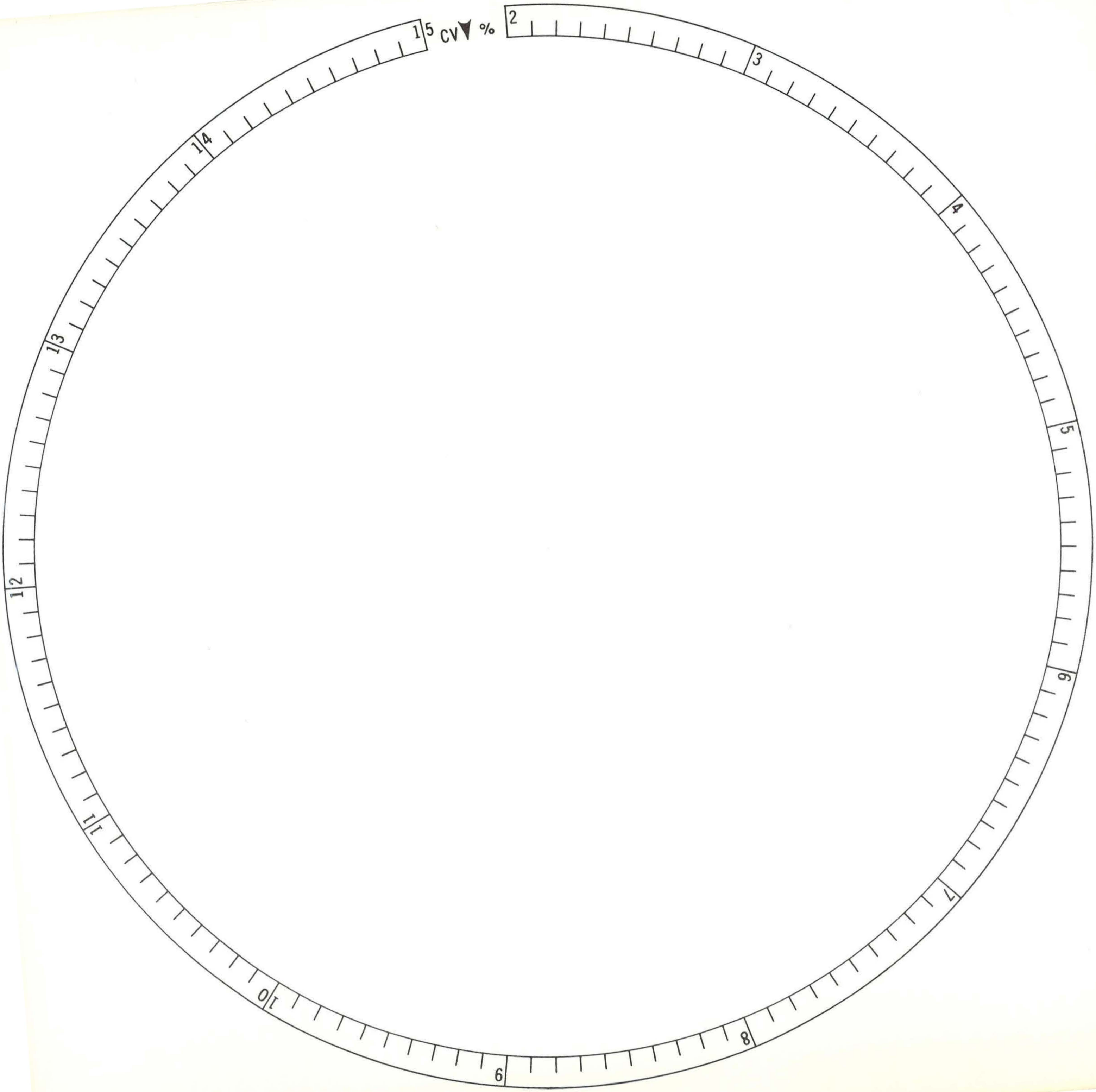
Assume that it is desired to estimate water retention of the soil on a watershed within 5 percent of the mean at the 95 percent confidence level. The inner scale is moved until the index arrows for suction and CV are aligned. The transparent index is then moved over the 5% mark on the outer scale.

There is now a choice of taking (1) four sample points with two subsamples at each point, (2) three sample points with four subsamples or (3), with slightly more risk, three sample points with three subsamples. For the conditions of our study, the second choice would be taken. However, if the field costs were less than experienced in this study (perhaps samples might be made with an auger rather than from soil pits) then the choice (1) might be more realistic.

The guide, of course, can also be used to estimate the precision that might be expected for limited cost. If the cost allowed is within the range of 12 to 14 man hours, then the precision that might be expected would vary from 4.65 to 5.59 percent of the increase.

Extra copies of the guide are attached.


SOIL SAMPLING GUIDE
TEXTURE
BULK DENSITY
COSTS TEXTURE
COSTS BULK DENSITY
COSTS SUCTION
SUCTION


CV %
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